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# The Lithology and Stratigraphy of the White River Beds of South Dakota

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# LITHOLOGY OF THE WHITE RIVER SEDIMENTS.

# LITHOLOGY OF THE WHITE RIVER SEDIMENTS.

Investigation aided by a grant from the Marsh fund of the National Academy of Sciences.

By HAROLD R. WANLESS.

(Plates IX. and X.)

(*Read April 22, 1922.*)

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## I. Introduction.

Since 1847, when the first White River fossil was described by Dr. Joseph Leidy, the abundant and varied fauna of this series, as exposed in the Big Badlands of South Dakota, has made it a center of interest for paleontologists and collectors. During the field seasons of 1920 and 1921 the writer has worked in this area with Professor W. J. Sinclair with the object of tracing the detailed faunal changes and determining, from the lithology of the beds, the conditions of sedimentation through the successive formations which make up the White River series. The work has been carried on in the Big Badlands south and southwest of the town of Scenic in Pennington County, and along the Wall of the Badlands north of Interior in Jackson County.

The earliest investigators assumed that most of the Tertiary mammal-bearing beds of the west were lake deposits, and that the excellent preservation of the skulls and skeletons they afforded was due to protection by water from subaërial weathering and disintegra-



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tion. Hatcher was among the first to suggest the possibility of a flood-plain of fluviatile origin instead of lacustrine, and evidence in recent years has been accumulating which supports his hypothesis. We are now able to recognize river-channel, fresh-water pond, sheet-flood, and eolian elements in the series. In the present investigation the writer has endeavored to draw from the lithologic characteristics of the sediments the sources of the material, the methods of transportation and deposition, and the physiographic and climatic conditions under which the White River faunas lived and evolved.

## II. Generalized Section of the Big Badlands.

To make the stratigraphic relations of the various types of sediments more clear, a generalized columnar section of the Big Badlands is presented in Figure 1, *C*, correlated with a section of the Oreodon beds from the Wall of the Badlands near Interior, about 40 miles to the east, and with Wortman's 1893[1] section, which has been generally used as the standard section for the district and is now somewhat in need of revision. The datum plane of correlation used is the top of the lower zone of rusty nodules or "Red Layer," as defined below. The stratigraphic elements of the White River series may be briefly indicated as follows:

1. *Titanotherium Beds.*—This zone consists of clay beds with numerous large sandstone channels. Thin limestone lenses are frequent throughout, but caliche zones are rare or absent. The subdivision of the Titanotherium beds into Upper, Middle, and Lower zones in Wortman's section is based on the supposed zonal distribution of titanotheres presenting different stages of horn development, as worked out by Hatcher.[2] A corresponding stratigraphic or lithologic subdivision has not yet been recognized and it is doubtful whether such will ever be possible. The thickness of the Titanotherium beds in the sections measured by our expeditions varies from 110 to 132 feet, which is somewhat less than Wortman's figure of 180 feet, though there are doubtless thicker sections than those measured by the writer, for the Titanotherium beds vary greatly in thickness from point to point, resting as they do on the very irregular erosion surface

[1] *Am. Mus. Bull.*, 5, 1893, pp. 98–9.
[2] *Am. Naturalist*, March, 1893.

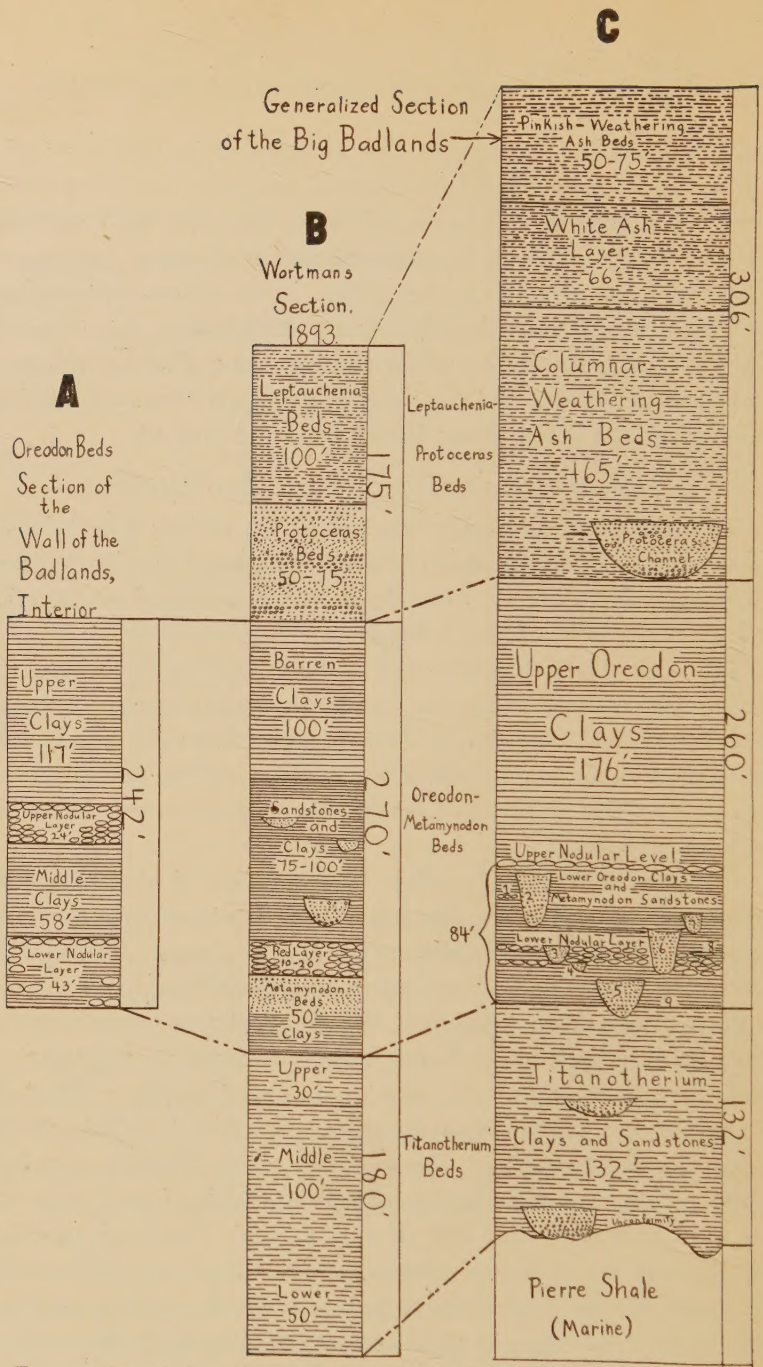


FIG. 1. Correlation diagram of sections of the White River formation. Section C: (1) algal ball horizon, Quinn Draw; (2) Metamynodon channel sandstone, Quinn Draw; (3), (4), (5) and (6) Metamynodon channel sandstones in Corral Draw; (7) Metamynodon channel sandstone, Little Corral Draw; (8) Solid sheet of algal limestone, Little Corral Draw; (9) Thin sheet of silicified limestone at base of Oreodon beds.

FIG. 1. Titanotherium beds topography as exposed in Indian Creek, Big Badlands. Note the rounded character of the hills. The Sheep Mountain section of Oreodon and Leptauchenia beds is seen in the distance to the left.

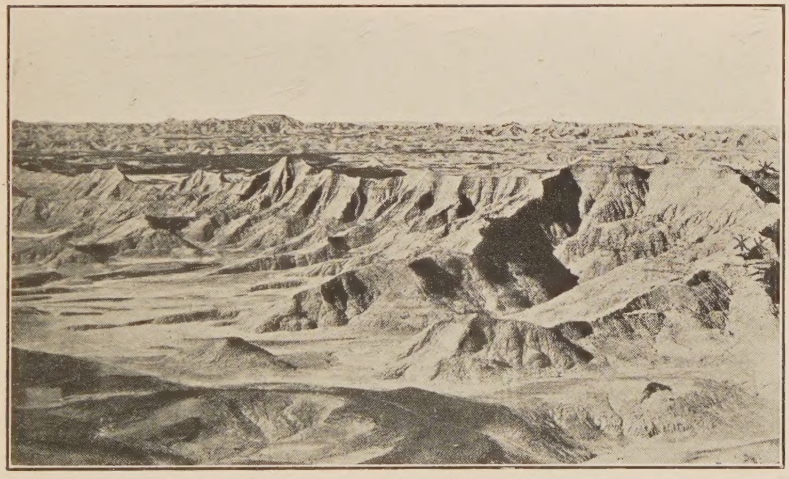

FIG. 2. Section of the Oreodon beds in Corral Draw, Big Badlands. The upper nodular level is marked (*), and the lower zone of rusty nodules or the red layer (**). Photo from the collection of the late S. W. Williston.

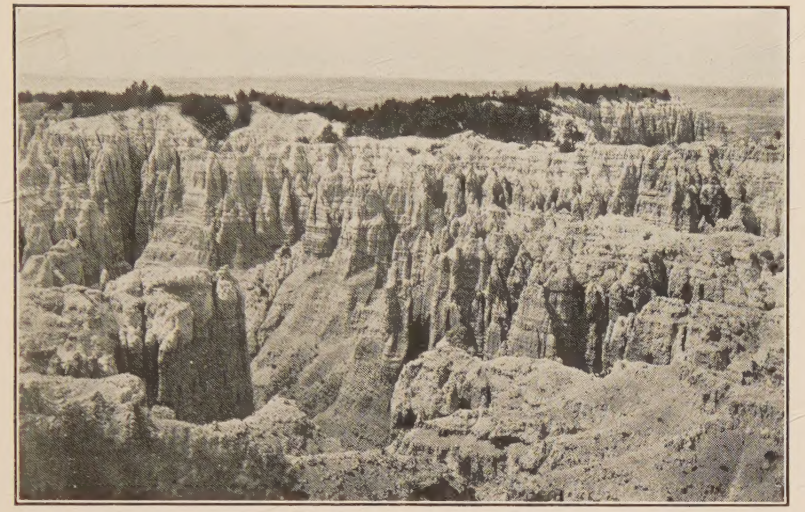

FIG. 1. Section of the Leptauchenia volcanic ash beds in a canyon of Sheep Mountain, Big Badlands. The top of the columnar vertical weathering in the picture is the top of division (*a*) of the Leptauchenia beds, as described in the text. Above this is the "white ash layer" of Matthew, division (*b*) of the text. This appears lighter colored than division (*a*), and does not show vertical columnar weathering.

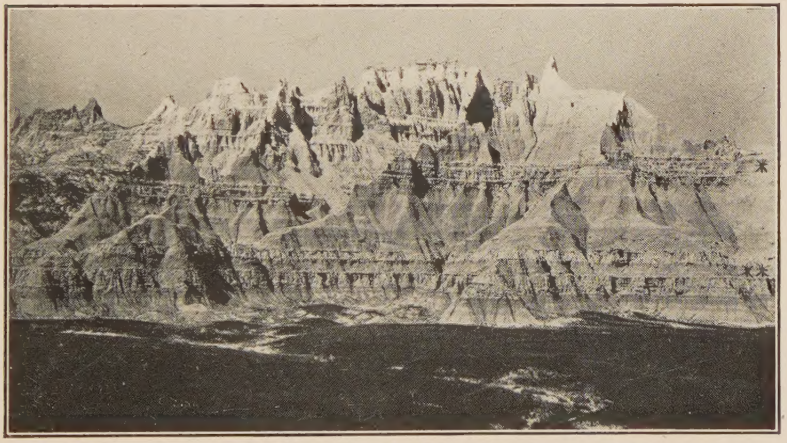

FIG. 2. Section of the Oreodon beds in the Wall of the Badlands at Cedar Pass, north of Interior, Jackson County. The central highest pinnacles are capped by Leptauchenia volcanic ash beds. The subdivision of the Oreodon beds here into upper clays, upper nodular layer, middle clays, and lower nodular layer are clearly shown, especially in the right half of the picture. The upper nodular layer is marked (*) and the lower nodular layer (**).

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of the Pierre shale. The lower part of the Titanotherium beds consists of blue and lavender clays made up entirely of reworked Pierre shale and affording calcareous nodules with cone-in-cone structure containing remanie Pierre shale fossils.[3] This lower zone is discussed below in connection with ground water circulation. The channels and limestone lenses are so numerous and, apparently, local that their stratigraphic positions have not been indicated in the generalized section.

2. *Oreodon-Metamynodon Beds.*—(*a*) Wall of the Badlands section. The Oreodon or Middle White River series as generally developed consists essentially of clays with local limestone lenses, interrupted by channels of coarse sandstone containing *Metamynodon.* In the "Wall of the Badlands" section near Interior (Fig. 1, *A*) they are divided into: (*a*) lower zone of rusty nodules and clays; (*b*) intermediate clay zone; (*c*) upper zone of nodules, more generally greenish than rusty; (*d*) upper clay zone. (See Plate II, Fig. 2.) The upper zone of nodules as here developed is absent in the Big Badlands and the same term is there applied to a thin caliche zone which is remarkably persistent over at least 200 square miles and may extend farther yet, but does not occur, or has not been identified, in the Interior section.

(*b*) Big Badlands section (Fig. 1, *C*). The base of the Oreodon beds in the Big Badlands is defined by discontinuous thin bands or lenses of silicified limestone or chert, ranging where present from two inches to one foot thick. This division plane was mentioned by Darton[4] when he first defined the Chadron and Brule formations. Where the limestones are absent the line of change in the weathering between the Oreodon and Titanotherium beds is used for the contact plane. The profiles developed on the Oreodon clays, as a rule, have steep slopes and a more angular appearance, while the Titanotherium beds weather with gentler slopes and more rounded surfaces. Plates I. and II. bring out this contrast clearly.

In the same area, the lower zone of rusty nodules, or so-called Turtle-Oreodon layer or "red layer," is defined by Sinclair[5] as beginning

[3] *Science,* Vol. 19, p. 254, 1904.

[4] Professional Paper, 32, U. S. G. S., p. 71.

[5] Proc. of the Amer. Philos. Soc., Vol. 40, 1921, pp. 457–466.

with the algal limestone or chert band at the base of the Oreodon beds and continuing upward from 29 to 43 feet (varying with the locality), generally overlain by a more greenish clay or nodule-bearing horizon much poorer in fossils than is the red layer. The red layer consists of pinkish clay with rusty-brown caliche nodules in fairly regular bands or irregularly distributed. In the Indian Creek sections usually from one to three nodule-bearing horizons are found in it, while in parts of Corral Draw as many as ten levels of nodules may occur. Elsewhere, as on Cain Creek, six miles east of Scenic, nodules are locally absent over large areas, and the whole lower Oreodon series consists of clays. As it is often impossible to tell at what part of the lower zone the nodules are developed it has been found that the upper layer discussed at greater length in the paragraph following makes a better datum plane than the lower zone. Both of these zones are very fossiliferous and the intervening clays from the upper nodular level to the base of the Oreodon beds have also produced many important fossils. Professor Sinclair's paper on the "Turtle-Oreodon layer or 'red layer,' a Contribution to the Stratigraphy of the White River Oligocene," which has just appeared, discusses primarily the lower nodular zone, and reference may be made to it for further details.

The upper level of rusty nodules is six inches to one foot thick and 80 feet, more or less, above the base of the Oreodon beds, or 40 to 60 feet above the top of the Lower nodular zone, the variation being due to changes in the thickness of the latter. As mentioned above, this thin zone of nodules is so widely distributed over the area of the Big Badlands that it makes the best datum plane in the whole series of the Oreodon beds. It has been clearly recognized at points separated by 25 miles (Arnold's Ranch district, 12 miles southeast of Scenic and Battle Creek Canyon, 30 miles southwest of Scenic) and may be found to have a still wider distribution.

The channels which cut the lower zone of rusty nodules are characterized by the presence of the large aquatic rhinoceros, *Metamynodon*, and are therefore called Metamynodon sandstones. They cut the Oreodon clays at various levels, but are most numerous between the upper level of rusty nodules and the base of the Oreodon beds. The stratigraphic position of six of these channels is shown in Fig. 1,

Section *C*, which also gives the position of a limestone lens in Little Corral Draw and an algal ball level in Quinn Draw.

The clays above the upper nodular level are generally alternate bands of pale pink and pale green beds with very few channels and nodular layers and no limestone lenses observed. The average thickness of this clay series in the Big Badlands is 160 to 170 feet, with a variation of not more than 10 feet in three sections measured 20 miles apart. This clay zone is less interesting because of its poorer fossil content and has not as yet been studied in much detail. Around the western and southern ends of Sheep Mountain this clay series is capped by a heavy sandy nodular layer about 50 feet thick, but this layer was not observed elsewhere.

3. *Leptauchenia-Protoceras Series.—A.* Protoceras Beds. The name Protoceras beds has often been applied to all of the Upper White River, but should be restricted to the stream channels cutting the so-called Leptauchenia clays, the former alone carrying a Protoceras fauna. No channels over 30 feet in thickness have been observed by the writer, and Wortman's figure of 50–75 feet is probably somewhat excessive. The position of these channels is generally at or near the base of the Leptauchenia beds. As the Protoceras sandstones are only formed in stream channels, many sections contain no Protoceras beds at all, the Leptauchenia horizon resting directly on the Upper Oreodon clays. It has been supposed that the Protoceras sandstones were deposited right in the stream channels where the current was strong, while the Leptauchenia "clays" were deposited at the same time in the quieter backwaters. In many samples of Protoceras sandstones, however, water-worn concretions are found, such as are very characteristic of the Leptauchenia beds. These concretions were sufficiently consolidated at the time of the Protoceras channels to be preserved as pebbles in the sandstones formed. This shows that the Protoceras channels were actually cut through the Leptauchenia beds and are thus younger than part of the latter zone. older Leptauchenia beds and are thus younger than part of the latter zone. This suggests contemporaneous erosion of the country rock by the channel forming streams.

*B.* Leptauchenia Beds. The most complete section of these is in

Sheep Mountain in the Big Badlands. They are subdivided in ascending order into:

(*a*) Vertical, columnar weathering, ash beds often affording abundant nodules somewhat resembling coprolites in shape and size. Each nodule has a vertical central tube around which the nodule seems to have grown by concentric accretion. The cementing material of these nodules has not yet been investigated. The general color of this division is pale pink. Thickness, 165 feet.

(*b*) A massive, white, volcanic ash layer at the top of the zone of columnar weathering, 66 feet thick. This and division (*a*) are shown in Plate II., Fig. 1. This zone is *more* resistant to weathering than (*a*), but does not show vertical faces.

(*c*) A capping of 50 to 75 feet of pinkish nodule-bearing volcanic ash beds, exposed on the highest parts of Sheep Mountain.

This gives a total thickness of 281–316 feet for the Sheep Mountain Leptauchenia beds section. If Matthew[6] is correct in correlating the Sheep Mountain "White Ash" layer with that exposed in the Porcupine Creek section of the Lower Rosebud Miocene, about 20 miles south of Sheep Mountain, divisions (*b*) and (*c*) of the above sequence may belong rather to the Lower Rosebud than the White River. This correlation is at present tentative and must be worked out by a more thorough study of both the stratigraphy and the faunal changes.

Additional stratigraphic details, it is hoped, may be presented in a subsequent paper.

## III. Method of Investigation.

The method pursued in the examination of the sediments is essentially that described by Crook.[7] A sample of 50 grams was selected for study and, in the case of the finer sediments, was crushed so that all of it passed through a one-millimeter mesh. This was done in order to allow the acid to act freely on all parts of the sediment, so that all of the calcareous cement would be dissolved. This was

[6] Matthew, *Bull. Am. Mus. Nat. Hist.*, Vol. 23, pp. 169–219, 1907.

[7] Hatch & Rastall, "Textbook of Petrology: The Sedimentary Rocks," 1913, pp. 339–414.

then treated with dilute hydrochloric acid until no effervescence followed the addition of more acid. The residue was then washed and dried at 110° C. and weighed, the difference representing the quantity of soluble cement. The residue was then placed in a beaker and water added to a level 9 cm. above the base of the beaker. This was allowed to stand 10 minutes, in which time all particles with a density of quartz or greater and a diameter greater than 0.01 mm. settled. The liquid with the mud was decanted and this process was repeated until the liquid was clear at the end of 10 minutes. The residue was then dried and weighed, the difference in weight representing the amount of mud in the sample. The residue was then decanted to remove silt. The sediment was covered with 14 cm. of water and allowed to settle for 20 seconds and decanted. This decantation was continued until the liquid was clear, some of the silt being saved for examination. The particles thus separated as silt have diameters of 0.01 to 0.1 mm. All coarser residues, when dried and weighed, represented the sand content of the sample.

In samples containing a noticeable percentage of heavy minerals, the sand residue was treated in a separatory funnel with Thoulet's solution (mercuric chloride and iodide dissolved in water) of a density of 2.95–3.0. By this method the rarer heavier minerals were concentrated and their amount and variety determined. From the heavy concentrate the magnetite was removed by an ordinary horseshoe magnet, and it was found that a fair concentrate of micas for study purposes, without attempt at quantitative separation, could be made by sliding the lighter sands repeatedly from a sheet of paper, where the mica flakes generally remained on account of their flatness.

The sands, silts, and heavy concentrates were then studied microscopically, with a series of liquids of known indices of refraction, and the individual minerals thus determined.

## IV. Types of Sediments.

In the sequence of sediments composing the White River series there are: (1) Stream-channel sandstones, represented by those of the Protoceras, Metamynodon, and Titanotherium levels whose relations to the surrounding clays can, generally, be easily deciphered. Due to the superior resistance to weathering of the sandstones, the

courses of old stream channels can often be traced clearly, sometimes by the crest of a high divide, sometimes by a marked ridge of sandstones across a modern creek valley.

(2) Fresh-water limestone deposits. These occur at various horizons through the Titanotherium and Oreodon beds and represent small pond or damp meadow deposits.

(3) Sheet-flood deposits. These constitute the bulk of the sediments of the Badlands and are normally clays not thoroughly consolidated, except where they have been old land surfaces for considerable periods, and have given rise to nodular or "caliche" beds by the drawing up of ground water to the surface where it evaporates, leaving its mineral content as a cement for the clays.

(4) Volcanic ash beds. The term "Leptauchenia Clays" is inappropriate, as the Leptauchenia beds consist essentially of pumice and volcanic glass fragments, connected with the eruptive action of the Cordilleran district during its Tertiary orogenesis. That this ash is probably wind-carried and water-laid, or, at least, reworked by water into essentially horizontal beds of sheet-flood deposition, is the conclusion reached from the strongly marked horizontal bedding of these beds, and the absence of cross-bedding.

(5) Eolian deposits. There are few traces of wind-blown sands in the White River in the area investigated, but one bed has been found in the lower part of the Leptauchenia series in the Sheep Mountain section which seems to be mainly a dune sand, and the sands of the Rattlesnake Butte sand calcite locality are apparently of dune origin, as described by the writer in another paper.[8]

These various types of deposition may now be discussed in somewhat greater detail.

### The Channel Sandstones.

Numerous typical sandstones from Titanotherium, Metamynodon, and Protoceras channels were examined. The amount of calcareous cement varied from 14 to 39 per cent., averaging about 25 per cent. In one sample of coarse Titanotherium sandstone, in addition to 26 per cent. of calcareous cement, the grains were found to be embedded in a matrix of chalcedony which may have constituted 10 or 15 per

[8] American Mineralogist, Vol. 7, No. 5. May, 1922.

cent. of the whole. Another sandstone sample, not directly connected with a channel, was nearly uncemented and crumbled readily in the hand. This showed only 2 per cent. of calcareous cement.

As for mineral composition, the grains show very definitely their derivation from the pre-Cambrian schists and pegmatites of the Black Hills. The quartz grains are ordinarily between 80 and 90 per cent. of the total sand and show frequent mineral inclusions, mainly biotite and tourmaline, which, according to Sherzer,[9] are, as a general rule, characteristic of gneisses and schists. The coarser sandstones contain a larger proportion of fresh, non-kaolinized feldspar than is found in the finer silts and clays of the series. Of the grains determined, microcline is the most abundant species; pink orthoclase is next in abundance and the plagioclase feldspars are quite rare, albite and oligoclase-andesine being determined. The feldspars averaged from 5 to 15 per cent. of the sands. Of the micas, white mica and brown mica (muscovite and probably biotite) are the most abundant, but green and black micas also are frequently present. The micas are most abundant in sands with small grains and evidently were laid down in quieter shallows away from the main current of the streams. They may total 1 or 2 per cent., but rarely more.

The heavy residues are more abundant and of larger grain in the coarser conglomeratic phases of the sandstones which contain occasional large quartz and feldspar pebbles. These were evidently formed where the current was strongest, as the finer sediment could not come to rest. The most abundant of the heavy minerals is a pink garnet which generally occurs in good rhombic dodecahedrons or combinations of these with tetragonal trisoctahedrons, or in sharp angular fragments of these crystals. In one sample where the heavy concentrate constituted 3 per cent. of the total sand, the garnet was nearly 90 per cent. of the concentrate. The other abundant heavy mineral is tourmaline, either the black massive variety of pegmatites (schorl) or very small, long prisms of dark brown and green color. The tourmaline never occurs in rounded grains in these sediments. Magnetite is present in some sands to 0.1 per cent. or occasionally more. It is usually in very fine well-rounded grains resembling in

[9] *Bull. Geol. Soc. America,* Vol. 21, 1910, p. 638.

appearance small particles of shot. Staurolite as angular, orange to brown grains is almost always present with the garnet. Other minerals identified in smaller quantities are: Augite (light green grains), rare; pyrite, very rare; hematite, apatite, and amblygonite (lithium phosphate). Other metallic nonmagnetic grains are perhaps cassiterite, wolframite, or columbite, all of which are common minerals of the pegmatite dikes of the Black Hills. In the coarser sandstones are found small pebbles of quartz-schist, quartz-sericite schist, and garnet-biotite schist, and a few pebbles of very fine-grained slates.

The evidence of the composition of the sandstones, as to the derivation of their material, is in full accord with the evidence of the direction of the channels, which lead away from the central granitic core of the Black Hills. Garnet, staurolite, the various schist pebbles, and quartz with inclusions point to derivation from the Algonkian schists and slates of this central core, and the tourmaline, amblygonite, and cassiterite (if present) point to derivation from the pegmatite dikes of the same district. The microcline, augite, and apatite are accessory constituents of the sands and may well have had a similar source.

The channels are evidently of different ages, as shown by their different stratigraphic positions in the accompanying sections, and some horizons seem to be cut by no channels through their whole visible extent. The upper nodular layer is an example of this.

A sample of the channel sand from the stream bed of Battle Creek, near Keystone, in the center of the Black Hills pre-Cambrian core, and within 5 miles of Harney Peak was collected and examined. It corresponds very closely in mineral composition to the stream-channel sands of the White River, but differs in the proportion of minerals present, and is generally of coarser grain, containing more garnets which may reach 30 per cent. of the total sand and more schist pebbles. This would be expected, as the stream is flowing through a garnet-mica schist terrane where the sample was collected. This may be regarded as confirmatory evidence of the Black Hills derivation of the material of the channel sandstones.

### Fresh-Water Limestones.

At various levels through the Titanotherium and Lower Oreodon beds are thin sheets or lenses of white limestones. These are some-

times in the form of algal ball levels made up of a series of flattened, oval-shaped balls which are often quite persistent. Elsewhere thin sheets of silicified limestones occur in which the original organic character has been almost destroyed by replacement by secondary silica. Such a sheet as this is sometimes quite persistent at the contact of the Oreodon and Titanotherium beds and, as elsewhere indicated, was used by Darton in defining the contact plane of these two horizons. A third type of limestone forms a lens-shaped solid sheet a few acres in extent. This type develops a limestone as much as 3 feet thick and is quite rich in organic remains, especially the shells of cyprids. This latter type undoubtedly represents a small pond on the surface of the flood-plain. Small pelecypods and gastropods are visible in this, but the fauna has not yet been described. It is believed that one reason for the silicification of the limestone is the solution of the siliceous shells of diatoms and replacement of the lime by this dissolved silica and also the solution of the limestone by ground water and replacement by colloidal silica. The fact that the limestone was in large measure formed by the action of fresh-water algæ was first suggested by Sinclair in 1920 for the algal ball type of limestone.[10] The presence of algæ has since been recognized in the other types of limestone mentioned above. The amount of lime in these beds is very variable, from 5 per cent. in the silicified cherty layer at the base of the Oreodon beds to 95 per cent. in one of the massive lenses of limestone.

The detrital material in the limestones showed the presence of fragments of quartz, biotite and tourmaline, and of pumice needles and angular volcanic glass fragments, suggesting that the detrital deposition in the ponds was probably by wind. It may be that the thinner sheets of algal limestone do not represent pond deposits, but were formed in moist meadow lands under prairie conditions.

### Nodular Layers.

The presence of nodular layers is of great interest to the palæontologist, as it is in them that vertebrate remains are best preserved. In some localities the nodules occur more or less isolated, but more often they are found as broad sheets and as such have a remarkable continuity.

[10] Amer. Philos. Soc., Vol. 40, 1921, p. 460.

The essential difference between the composition of the caliche levels and that of the other parts of the clay series is in the proportion of calcareous cement. Samples of the upper and lower zones of rusty nodules analyzed gave, respectively, 51 and 37 per cent. soluble calcareous cement. A nodular layer (not caliche) of more sandy character, but of uncertain origin, in the upper 50 feet of the Oreodon beds, exposed only in the Sheep Mountain sections, contains 30 per cent. of soluble cement. The average amount of soluble cement of the clays of the White River series is from about 5 per cent. in the Titanothere beds to 15 per cent. in parts of the Oreodon series. The caliche nodular layers were doubtless cemented at or near the surface by ground water rising by capillary attraction and depositing the calcium carbonate when it evaporated. Thus the bones of animals which happened to be near the surface at this time were protected from disintegration. The clay forming the nodular layers was originally a fine-grained flood-plain deposit which persisted as a land surface for a considerable period of time and probably indicates a period of greater aridity, by reason of the breaks in deposition, evidence of evaporation, etc. The nodular layer has in the presence of coprolites of carnivorous animals and rodent-gnawed bones absolute proof of subaërial deposition. Many of the bones found are also of a decidedly weathered appearance much as are bones of modern animals weathering on the surface of the Badlands today and occasionally buried in silt. Further proof of subaërial deposition was recently found during the preparation of a *Cœnopus* skull collected in the lower zone of rusty nodules, a large number of casts of insect larval burrows being found within and around the skull, suggesting that it had lain on the surface for some time before burial and the meat had been devoured by the scavenging insects, which subsequently burrowed for pupation in the mud investing the skull. It has not been possible yet to determine to what form these insects belonged. The great continuity of the nodular layers, which has been mentioned above, implies a very level surface controlling evaporation, which was cut here and there by shallow winding stream channels, which may have carried running water only in flood time. A uniform climatic factor, probably a period of greater aridity, was one of the most im-

portant elements in the formation of the caliche nodular levels. The part which climate played in the color-banding of the Oreodon clays has not yet been determined.

The clays making up the nodular layers resemble the normal clays very closely. They contain very finely divided silt from the decomposition of the feldspars of the Black Hills, and small angular fragments of quartz of a size smaller than the lower limit of rounding by water. Flakes of brown mica are frequently seen. Fragments of pumice and volcanic glass were recognized in all samples studied and sometimes make up an appreciable per cent. of the total clastic material. These were wind-carried and water-laid, as demonstrated by the marked horizontal bedding of the nodular layers and the absence of cross-bedding.

### Volcanic Ash Beds.

The Leptauchenia beds consist largely of a well-consolidated white fine-grained rock, which weathers with a marked vertical columnar appearance, giving rise to sheer cliffs up to 200 feet high. This seems to consist very largely of volcanic glass and pumice. The pumice shows numerous capillary tubes in parallel arrangement which are sometimes deformed by flowage (indicated by strain polarization). There are also throughout the mass long hair-like needles with capillary tubes in the center resembling superficially Pele's hair. With the material of volcanic derivation there are also small fragments of mineral matter of the texture of silts. The grains are not rounded and are mostly too small to be rounded by water. Quartz and biotite are the most common of these mineral fragments, and feldspars and tourmalines were also recognized. A sample of the sand from the White Ash layer, division (*b*) of the beds as described above, which contains about 90 per cent. glass or pumice fragments, was analyzed by Professor A. H. Phillips, of Princeton University, with the following result:

| | | | |
|---|---|---|---|
| $SiO_2$ | 68.21 | MgO | 1.13 |
| $TiO_2$ | 0.32 | $K_2O$ | 4.41 |
| $Al_2O_3$ | 10.97 | $Na_2O$ | 3.13 |
| $Fe_2O_3$ | 2.89 | $P_2O_5$ | none |
| FeO | 0.13 | $H_2O > 110°$ | 5.01 |
| MnO | 0.12 | $H_2O < 110°$ | 3.05 |
| CaO | 1.08 | | 100.45 |

Calculated in terms of norms as described by Iddings,[11] this glass is a rhyolite with the following standard mineral composition:

| | | | |
|---|---|---|---|
| Orthoclase | 28.36 | Diopside | 2.38 |
| Albite | 28.82 | $MgSiO_3$ | 2.00 |
| Anorthite | 2.78 | Ilmenite | 0.60 |
| Quartz | 31.93 | Hematite | 3.13 |

In some specimens of these ash beds small cavities and irregular cracks are lined with needle-like crystals of a zeolite, apparently mordenite, of the composition $(Ca, Na, K)_2Al_2Si_{10}O_{24} \cdot 6\frac{1}{2}H_2O$, with a mean index of refraction of 1.465 and a very low double refraction, about .005. This was probably formed as a result of slight hydrometamorphism by alkaline solutions deriving their soluble content from the volcanic ash on which they reacted. There is little chance of thermal metamorphism, as the ash should have been thoroughly cooled after transportation several hundred miles in the air. The cavities in which these zeolites have crystallized are not solution cavities, but more probably shrinkage cracks. The index of refraction of the glass and pumice was found to vary between 1.495 and 1.505. The composition of the zeolite is very similar to that of the ash, and it is probably a recrystallization of material derived from the glass and pumice.

In making the analysis of the ash, Professor Phillips found that after being dried at 110°, to remove the absorbed moisture, on standing in the air the ash took up about 3 per cent. of water very readily. This strong hygroscopic character is probably due to the attraction of the capillary tubes of the pumice fragments for water, and may account in part for the resistance to weathering of the ash beds, as described above.

### The Clay Beds.

The greater part of the White River formation is not made up of the more interesting types already described, but rather of very fine silt horizontally bedded and color-banded pale pink or brown and pale green. These constitute all of the Oreodon and Titanotherium beds except the nodular layers, channel sandstones, and limestone lenses.

Their minerals are generally so fine grained as to be difficult of determination, but fine angular fragments of quartz, more or less

[11] "Igneous Rocks," Vol. I., pp. 435 on.

weathered feldspars, and mica foils can be detected in all samples, as well as occasional fragments of pumice and volcanic glass. The latter fact shows that showers of volcanic dust were being deposited throughout White River time, but first became the dominant source of sediment at the beginning of the Leptauchenia beds stage. The clay beds represent the normal sheet-flood deposits of a level country and probably are mainly formed of kaolinized feldspars from the granites and pegmatites of the Harney Peak mass, as well as from decomposition products of other minerals less stable in the zone of weathering.

As mentioned above, the profiles developed on the Oreodon clays, as a rule, have steeper slopes and a more angular appearance than those developed on the Titanotherium beds which weather with gentler slopes and more rounded surfaces. The chemical tests suggest that this is due to a difference in the amount of calcareous cement in the two series. The samples of the Oreodon clays averaged 10 to 12 per cent. soluble cement, while the Titanotherium clays averaged only about 4 per cent.

### V. Evidence from Shapes of Sand Grains.

Inasmuch as the method of transportation and deposition of sands can often be definitely established by the shapes and average sizes of sand grains, a study of this feature of the White River sands was attempted.

The channel sands, as a rule, have large rounded grains, but the smaller grains are almost all angular and with sharp conchoidal fracture. This is because grains with a diameter less than 0.1 mm. are coated, while submerged, with a film of water which prevents one grain coming into physical contact with another, and thus prevents abrasion. On the other hand, the air forms no such cushion for the smaller grains, and thus wind-rounded sands may show rounded grains down to the finest sands present. The only sample of sand found in the White River which showed thorough rounding even to the finest particles is a fine-grained sandy silt occurring 11 feet above the base of the Leptauchenia beds in the Spring Draw section, Sheep Mountain. This sand has well-rounded grains even in the smallest sizes and contains a notable amount of magnetite and green horn-

blende, minerals which were not abundant in the ordinary channel sands. The garnets contained in the sand are also well rounded. This bed, which is apparently thin and local, evidently represents dune sand deposition. The sands rounded in stream channels have bright surfaces, while those rounded by wind action generally are dull or show etched or pitted surfaces. The sands of the base of the Leptauchenia bed in the Sheep Mountain section, mentioned above, show dull and pitted surfaces, confirming their eolian origin.

Another excellent example of round-grained dune sand of later age than White River is found in the sand grains of the sand-calcite at Rattlesnake Butte, Washington County. The crystals contain about 37 per cent. calcite, crystallizing as perfect scalenohedrons, and contain perfectly rounded sand grains down to the finest present. The quartz approaches spherical shape, the feldspars are generally larger grains and not quite so well rounded. The pink garnets are round. The green hornblende grains are nearly all elliptical in outline, prisms with the corners rounded. Zircon appears as fine yellow grains, about one fourth the size of the average quartzes. Round fragments of volcanic glass have also been found in this sand. The surfaces of the grains have a dull or ground-glass appearance due to wind abrasion.

By a study of part of the White River in eastern Colorado, Matthew[12] came to the conclusion that the White River was largely of eolian origin. A sample of silt from the Oreodon beds of Lewis Creek, Colorado, in the area investigated by Matthew, was examined by the writer and was found to consist largely of fine dust with much volcanic material (pumice and glass) and some of the quartz grains well rounded. It was evidently mainly of eolian origin. Matthew points out that in much of the fossil material from the White River of northeastern Colorado the "hollows in the bones (such as the cellular hollows in the skull . . ., the tympanic bullæ . . ., etc.) are still empty, never having been filled by mud or crushed in."[13] He points out that this could not happen if the bones were fossilized in such a body of water as a lake, as the weight of water and overlying sediment would either fill in the cavity with mud or crush the skull.

[12] Matthew, *Am. Naturalist*, Vol. 33, 1899, pp. 403–408.

[13] Matthew, *Am. Mus. of Nat. Hist. Memoirs*, Vol. I., p. 365.

Thus it seems that while the White River may be mainly of eolian origin in Colorado as Matthew has decided, it was mainly deposited by fluviatile agents in the South Dakota section. The writer's conclusion is that in the sections of the Big Badlands investigated eolian deposition is unimportant, though locally present.

## VI. Evidence of Ground Water Circulation.

Though the clay beds of the Badland district seem to be nearly impervious to water, there are abundant evidences of deposition and replacement by the action of ground water. The formation of caliche nodules by deposition of calcareous cementing material with the evaporation of the water at the surface has been referred to.

Throughout the Big Badland district are veins of blue chalcedony in vertical cracks in the clays. These were probably deposited in shrinkage cracks. Other fissures filled with sandy silts or sandstones occur frequently through the Badlands, but most abundantly in the Leptauchenia beds. These filled fissures are often more resistant to weathering than the surrounding clays and stand out in relief as sandstone dikes. Often the sandstone dikes were bordered on each side by chalcedony veins, and in one case there were two or three veins of chalcedony on the same side of the dike, indicating repeated opening of the fissure. The chalcedony veins ordinarily vary in thickness from one quarter inch to three inches and show evidence of gradual filling of the cracks from the two walls. Sometimes the whole vein is silica, but in many cases, specially in the wider veins, well-formed crystals of calcite have formed in the center of the vein, evidently as the last stage of deposition. Sometimes the center of the vein remains open. Occasionally large bell-shaped concretions of chalcedony up to a foot in diameter are formed in the clay. Chalcedony of similar nature is found filling the marrow cavities of fossil bones and the pulp canals of teeth. An interesting case was noted by the writer in a bone in which the lower part of the marrow cavity was filled with fine silt, evidently worked in soon after deposition, and the rest of the cavity was filled with chalcedony. In several cases chalcedony veins were found to cut directly through fossil skulls. Generally no hardening of the clays adjacent to the chalcedony veins is observed, showing that the deposition was from cold water. Some

diffuse cementation of the clays by colloidal silica in the vicinity of chalcedony veins is occasionally noticed, rapidly wearing the edge off the chisel used in the preparation of a specimen.

In many places the basal titanotherium beds contain a series of about 30 feet of clay of blue, lavender, and pink colors when fresh, weathering to a limonite brown and hematite red. This clay is clearly derived from a reworking of the Pierre shale material and even contains Pierre shale fossils, as Baculites, Inoceramus, etc., which are remanie or redeposited as first reported by Loomis.[14] In places where this series is absent, the silts or sands resting directly on the Pierre shale are almost always colored a bright pink color, and on examination the clay particles are seen to be strongly colored by the red oxide of iron.

The uniform presence of these iron-colored beds at the base of the more or less pervious Titanotherium beds and directly above the impervious Pierre shales is evidently a case of iron dissolved out of the White River series and redeposited and concentrated at the limit of downward circulation along the Pierre shale contact.

## VII. Conclusions Drawn from the Lithogenetic Evidence.

From the evidence above presented one can draw a fairly good picture of the physiographic conditions at the time of the deposition of the White River beds.

The country was very level, with a gradual slope away from the Black Hills uplift, as evidenced by a slight initial southeast and easterly dip of the beds. The Black Hills were probably still being elevated, but already were sufficiently high and eroded to furnish clastic material from the pre-Cambrian central core.

Fairly sluggish streams meandered across the plain in shallow channels and frequently spread widely out upon the plain when in flood, depositing thin sheets of fine silt. Gradually increasing volcanic action in the Cordilleran region and perhaps in the northern Black Hills furnished a growing supplement to the clastic material from the hills, until in the Leptauchenia stage this source became predominant. It is possible that the statements of Ransome, Schuchert, and others that the Oligocene represents a lull in the uplift and

[14] *Science,* Vol. 19, p. 254.

vulcanism through the Tertiary Cordillera between the periods of storm of the Eocene and Miocene will have to be amended. The presence of a 200-foot bed mainly of volcanic glass and pumice 80 miles away from the nearest possible source of volcanic ejecta, and more likely 200 to 400 miles distant from the eruptive volcanoes, would hardly seem to indicate a period of quiet. Professor Sinclair's description of a considerable thickness of andesitic tuffs and breccias of Titanotherium beds age in the Wind River Basin of Wyoming south of the Bridger-Owl Creek Range, is interesting in this connection.[15]

The only evidence of vegetation found fossilized so far in the Big Badlands are a few hackberry seeds (Celtis), but Hatcher reports the remains of a forest 12 miles north of the mouth of Corn Creek. The plain was here and there dotted with small ponds in which freshwater algæ and cyprid crustaceans were building up the limestone beds of the series.

Thus we have a general picture of the environment of one of our finest Tertiary mammalian faunas.

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[15] *Bull. Am. Mus. Nat. History*, Vol. 30, 1911, pp. 99–102.

# THE STRATIGRAPHY OF THE WHITE RIVER BEDS OF SOUTH DAKOTA.

# THE STRATIGRAPHY OF THE WHITE RIVER BEDS OF SOUTH DAKOTA.[1]

By HAROLD R. WANLESS.

(*Read April 20, 1923.*)


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[1] Investigation aided by a grant from the Marsh Fund of the National Academy of Sciences.



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## I. Introduction.

In an earlier paper the writer published the results of a microscopic study of the sediments of the White River series in the Big Badlands of Pennington and Washington Counties in southwestern South Dakota, and discussed the various types of sediments represented in this area. The clastic sediments of the White River beds were there shown to be, in large part, derived from the Black Hills uplift, which lies about 50 miles to the west of the Big Badlands. The abundance of wind-blown volcanic ash in the upper part of the White River beds was also pointed out.

The present paper aims (1) to present a stratigraphic study of the various formations of White River age in the same area, with a description of several well-distributed sections, showing the vertical succession of the various types of sediments discussed in the earlier paper; (2) to make certain changes in the sections published in the previous paper as the result of the subsequent discovery of a few definite horizon markers of wide geographic distribution; (3) to show the remarkable continuity and uniformity over immense areas of certain members of the White River series; (4) to present in outline the successive interpretations given to the climate and physiography of White River time by geologists of the past 70 years, with a critical discussion of their views; (5) to interpret the climatic and physiographic significance of the various types of sediments observed in the badlands, based upon their lithologic character, the presence of concretions and other structures, and the conditions under which fossils of White River time are found preserved; (6) to present an outline of the physiographic and climatic changes to which the area of the Big Badlands has been subject between the withdrawal of the Cordilleran sea of Cretaceous time and the close of White River deposition, as these changes are represented by sediments or erosional unconformities; (7) to deduce from the distribution of volcanic ash of White River and Lower Miocene date the source of the volcanic material and some measure of the magnitude of the eruptions which supplied this ash; (8) to attempt an explanation of the relations between sandstone dikes and chalcedony veins, the silicification of limestones and gypsum beds, and the development of caliche layers, accept-

FIG. 1. Sketch map of a portion of the Big Badlands of South Dakota, showing the distribution of the table lands and other remnants of the high plain (horizontal shading), dune sand deposits (light dots), and pre-Cheyenne River gravel channels (lines of heavy dots), and the positions of the columnar sections (*A–H*). Adapted from Map of Interior District (White & Campbell), Map of the Pine Ridge Indian Reservation (Dept. of the Interior, Office of Indian Affairs, 1914), and Map of the White River Badland Formations of the Black Hills Region (O'Hara, 1920). Scale 1/570240. (9 miles = 1".)

ing the theory that the fissures which are occupied by these dikes and veins were formed by desiccation; and finally (9) to present briefly some evidence on the stages of post-Oligocene erosion and deposition and climatic change in the area, and to suggest explanations for some of them.

It is the hope of the writer that this paper may establish a standard section of the White River formations in their type locality, which will be of value in correlating the elements of the White River in other districts.

The field and laboratory work upon which this paper is based has been done under the direction of Dr. W. J. Sinclair, of Princeton University, who has given the writer the benefit of his broad experience with western Tertiaries in passing on various theories developed to explain relations or structures observed in the field. The field work was done during the summers of 1920, 1921, and 1922, under the auspices of the Department of Geology of Princeton University, assisted by a grant from the Marsh Fund of the National Academy of Sciences. Dr. A. H. Phillips kindly analyzed a sample of the clays of the "Interior" beds and has given valuable assistance in interpreting some of the chemical problems involved. Dr. A. H. Pillsbry, of the Philadelphia Academy of Sciences, has identified some of the fresh-water and land invertebrates found in the White River, and Dr. R. W. Chaney, of the Carnegie Institution, has studied some petrified wood collected in the Titanotherium beds and supplied the writer with data on the climatic range of *Celtis*. The writer is also indebted to Professor W. B. Scott and to the late Mr. T. B. Lawler, of Princeton University, for frequent helpful suggestions, and to Mr. J. B. Mawdsley for assistance in the preparation of some of the illustrations.

## II. Stratigraphy.

*Pierre Shale.*—The Pierre shale underlies the White River formations throughout the area of the Big Badlands. It is everywhere a gray shale which weathers very easily to a dark gray or black mud. Even fresh samples are so soft as to be easily broken or crumbled between the fingers. Bedding is not visible in the Pierre except where it is emphasized by levels of concretions. The Pierre contains

a rich marine Cretaceous fauna, and at almost any outcrop fragments or shells of *Inoceramus, Baculites, Scaphites, Placenticeras,* and other forms may be discovered with a little search, the original thin pearly iridescent outer layer being frequently preserved. Crystals of gypsum occur abundantly in this shale and springs emerging from it are strongly impregnated with sodium sulphate. At various levels there occur large round or flattened oval siliceous concretions, which contain marine fossils more abundantly than does the rest of the shale.

*The Interior Formation of Ward.*[1]—The surface of the Pierre shale upon which the White River deposits rest is very irregular. In the area of the Big Badlands the maximum relief of this surface may be from 50 to 100 feet, though no exact figures are available. It is possible that later formations may have been deposited in this area and subsequently removed by erosion. At many points in the Big Badlands there is a gradational change from the dark gray alkaline shales of the Pierre to the greenish clays and silts of the Titanotherium beds. This zone of gradation has a thickness of 38 to 45 feet and consists of lavender and blue clays, weathering to a rusty brown color diversified by calcareous nodules with cone-in-cone structure and concentrically banded nodules of pink or red color strongly impregnated with oxides of iron, each type of nodules being developed along definite horizons. In other sections the contact between the Pierre shale and the Titanotherium beds is abrupt, a thin bed of pebbles of quartz, feldspar, and igneous and metamorphic rocks derived from the pre-Cambrian of the Black Hills, resting immediately on the shale. Where the blue and lavender clays are absent the sands and silts which occur at the very base of the White River formation are stained an ochre yellow by saturation with hydrated oxide of iron. This is a local hardpan formed by the ground water where the impervious shale limits further downward circulation.

These lavender and blue concretionary clays have been named the "Interior formation" by Professor Ward in a recent paper,[2] because of their development in the vicinity of Interior, Jackson Co., South Dakota. He believes that the color is primary, and that these clays represent the Fox Hills, following without break after the Pierre.

[1] South Dakota Geol. and Nat. Hist. Survey, Bull. 11, pp. 18–20.

[2] Ibid.

Professor Toepelman[3] suggests that "they may be a slightly sandy phase of the Pierre, such as are now being made known from many localities with the typical blue-black color of the shale, and have subsequently been changed in color through the process of weathering and the circulation of waters from the overlying Tertiary." Three vertebræ in articulation, probably mosasaurian, were found in the clays of the "Interior" beds by the Princeton 1922 expedition in the valley of Bear Creek 2 miles north of Scenic. Loomis[4] discovered a large Pierre fauna in these clays in Spring Creek, west of Scenic, and at lower levels some *Titanotherium* bones in place, indicating that a part of the material had been reworked and that some of the Cretaceous fossils might be remanie.

In the "Interior" formation at several points flattened, convex, lens-shaped concretions with an average diameter of 2 to 3 feet and an average thickness of a foot to 18 inches are developed. These are colored a light chocolate brown and show cone-in-cone structure along the top and bottom in bands about 4 to 6 inches thick. These concretions often contain in their centers weathered casts of the shells of *Baculites* and *Inoceramus*. Loomis[5] has published a list of fossils found in the Interior beds in Spring Creek, many of which are from these cone-in-cone concretions. An analysis of some of the cone-in-cone material showed 73 per cent. of soluble carbonates, presumably $CaCO_3$. Tarr[6] has discussed the origin of cone-in-cone and assigns it tentatively to pressure phenomena developed by the recrystallization of aragonite to calcite. Similar concretions occur along regular horizons, and at various levels through the Pierre shale,[7] and their origin is probably not a part of the White River problem.

In the upper part of the Interior formation are one or two levels characterized by rounded or flattened oval concretions which in section are seen to be formed about a clay center, and show concentric bands of varying shades of brown, colored by hydrated oxides of iron. A test showed a very small percentage (less than 3 per cent.) of cal-

[3] Ibid., p. 64.

[4] *Science*, N. S., Vol. 19, p. 254, 1904.

[5] Ibid.

[6] *Am. Jour. Sci.*, 5th Series, Vol. IV., pp. 199–214.

[7] "W. A. Tarr, "Syngenetic Origin of Concretions in Shale," *Bull. Geol. Soc. Amer.*, Vol. 32, 1921, pp. 373–384.

careous cement in these concretions. Their origin is not clear, but they seem to represent a product of concentration formed on an old land surface with the help of cementation by iron compounds in the ground water. Pilgrim,[8] in speaking of concretionary layers in the Siwaliks, describes them as pseudo-lateritic in origin, and it is believed that these also may have been formed in a laterite. No fossils have been discovered in this type of concretion.

An analysis of a sample of the lavender clay of the "Interior" beds from the valley of Bear Creek, 2 miles north of Scenic, by Professor A. H. Phillips follows (1), contrasted with an analysis of the typical Pierre shale (2) from Pueblo, Colorado:[9]

| | (1) Lavendar Clay of "Interior" beds, Bear Cr., 2 miles north of Scenic, S. D., Phillips, analyst. | (2) Tepee Zone of Pierre Formation, Pueblo, Colo., Steiger, analyst. |
|---|---|---|
| $SiO_2$ | 61.20 | 60.80 |
| $TiO_2$ | .58 | .47 |
| $Al_2O_3$ | 18.75 | 15.63 |
| $Fe_2O_3$ | 4.39 | 4.52 |
| FeO | .73 | .... |
| MnO | .06 | .... |
| CaO | .37 | 1.63 |
| MgO | 1.06 | 2.73 |
| $K_2O$ | 3.83 | 2.55 |
| $Na_2O$ | 1.59 | 1.45 |
| $P_2O_5$ | .09 | .10 |
| $H_2O < 110°$ C. | 2.73 | 3.19 |
| Loss on Ignition | 4.72 | 4.16 $H_2O > 100°$ C.<br>2.87 Organic. |
| | 100.10 | 100.20 |

The noteworthy features of the chemical composition of the "Interior" clays are: (1) that the total percentage of iron oxides is somewhat higher than in the underlying Pierre; (2) the percentages of lime and magnesia are notably lower; and (3) the percentage of potash is considerably higher than that of the Pierre. The proportion of iron oxides given is lower than the average for the "Interior"

[8] Records of Geol. Survey of India, Vol. XLII., Pt. 4, 1913.

[9] U. S. G. S., Geol. Atlas of the U. S. Pueblo Folio No. 36, p. 7.

FIG. 1. Divisions 4 (foreground) and 5 of the Oreodon beds, with overlying Leptauchenia beds, along the edge of Cooney Table in Battle Creek Draw. Marginal numbering corresponds to divisions in Text Fig. 5, A2, and Text Fig. 9A.

FIG. 2. Contact of Pierre shale (dark beds in lower half of picture) and Titanotherium beds, at main forks of Indian Creek.

beds as a whole because of the levels of concretions rich in hydrated ferric oxides in the upper part of the series. Concentration of iron and potash and diminution of the lime and magnesia content are characteristic results of weathering and leaching, suggesting that the "Interior" formation represents the less soluble materials of overlying beds, which were eroded before White River time.

The relation of the "Interior" beds to the Pierre shale is an interesting problem. The wide distribution and uniform thickness of the "Interior" beds lead Ward [10] to believe that their peculiar characteristics are primary, and that they were deposited at a stage of the withdrawal of the great Cretaceous Cordilleran sea. He writes: "The most rational view seems to consider the material to have originally been just as different from the typical Pierre as it is seen to be today. Then follows the interpretation of a shallowing sea, a nearer shore line, a changing geography, an accompanying diastrophism."

The writer is inclined to agree with Toepelman in his opinion, cited above, that the color is secondary and due to the concentration of iron from the erosion of the Pierre and overlying beds during Eocene, or at least pre-White River time. The peculiar characters of this bed and its wide distribution below the Titanotherium beds lead the writer to believe that it was formed rather by weathering and leaching on the surface during a long period of pre-White River erosion than that its characters are primary as Ward suggests. It is unlikely that a bed as thin as this would happen to be the surface on which deposition began over a wide area, after a period of erosion as long as that from the later Cretaceous to the Oligocene. The thickness of this bed, 38 to 45 feet, suggests that weathering and iron impregnation took place to that depth. Such deep weathering is characteristic of warm and humid climates, hence the period of formation of the Interior type of clays may have been warm and subhumid. The surface of the "Interior" formation seems to have been essentially a peneplain, for it shows only minor irregularity. In the upper part of the Interior formation, besides the concentrically banded iron concretions described above, there are found numerous narrow veins (½ to 2 inches in width) filled with limonite. As

[10] Op. cit., p. 19.

ferric iron is a comparatively rare constituent of the Pierre shale (about 2 per cent.), this abundant occurrence of it near the old surface may represent the erosion of a considerable thickness of later beds with concentration of their iron content. Some of this iron may have been leached out of the overlying White River clays and precipitated where the downward circulation of water is stopped by the impervious Pierre shales.

As pointed out above, in some sections of the Big Badlands the "Interior" beds are absent, and the White River (Titanotherium) sands and silts rest directly upon the Pierre shale. The north branch of Indian Creek, about 4 miles southwest of Scenic in Pennington Co., shows sections where the Interior clays are present and others where they are absent. Two sections in Indian Creek (*G*) and (*H*) and one in Bear Creek valley 3 miles northeast of Scenic (*F*), (near the locality where Thaddeus Culbertson made the first collection of badland fossils in 1850), whose geographic positions are given on the map, Fig. 1, are presented in Fig. 2. It will be observed that the thicknesses of Titanotherium clay overlying the Interior beds in (*F*) and (*G*) are, respectively, 72½ and 71 feet. In (*H*), where the Interior beds are absent, the normal gray clays of the Titanotherium beds are 73 feet thick, and below them are 10 feet of channel sandstone, 49 feet of irregularly banded pink clays and green silts, and a thin basal conglomerate. The great uniformity in thickness of the Titanotherium beds above the level of the "Interior" beds (71, 72½, and 73 ft.) indicates that deposition of the later Titanotherium beds began on a plain in which the streams flowed in shallow channels, thus continuing the peneplain of erosion of which the "Interior" beds are the surface. For convenience this may be termed the Interior peneplain. The 60 feet of silts, sands, and gravels of Titanotherium age deposited below the level of the top of the "Interior" beds (Fig. 2, Section *H*) were evidently laid down in valleys which had been cut below this peneplain shortly before the beginning of White River time. In the north branch of Indian Creek, about ½ mile south of E. H. Taylor's ranch on Hart Table, one passes abruptly within 100 yards on the same contour from a section of 40 feet of Interior clays to 50 or 60 feet of Titanotherium silts, sands, and

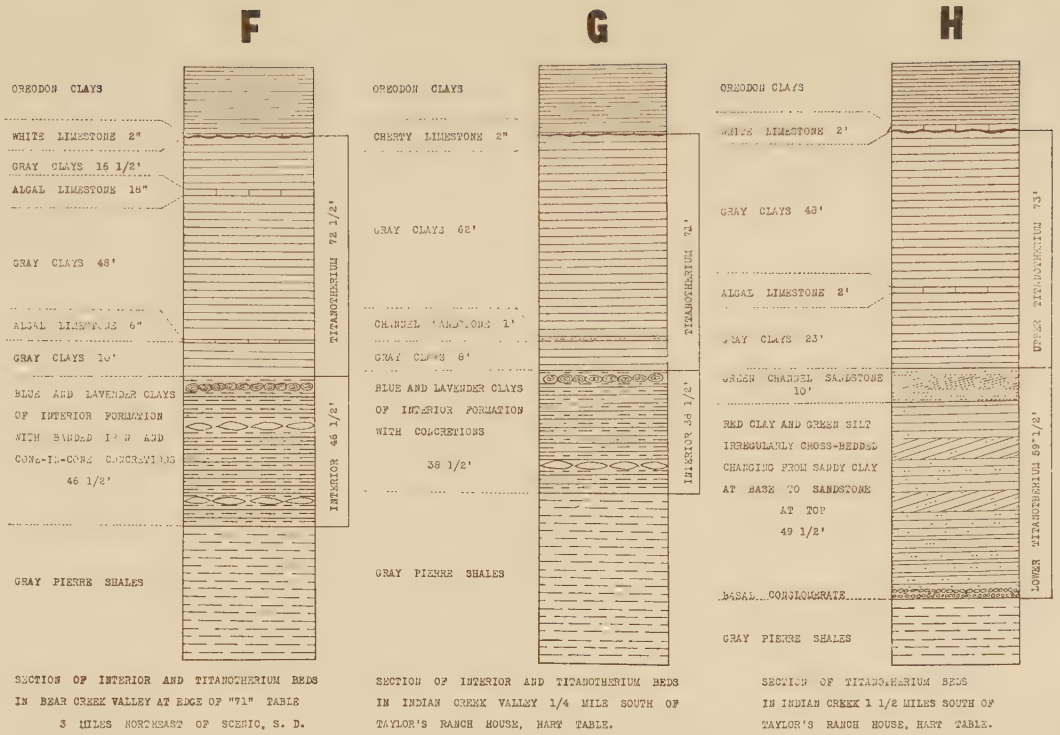



FIG. 2. Parallel columnar sections of the Titanotherium and "Interior" formations in the vicinity of Scenic, S. D. (*F–H* on the map, Fig. 1.) Vertical scale 60′ = 1″.

gravels. This indicates that the walls of the valley were quite abrupt. Pre-White River erosion in the north branch of Indian Creek had evidently removed the "Interior" beds and cut 15 or 20 feet into the underlying Pierre shale. Farther south (toward the center of the valley), where a massive sandstone 20 feet thick with a thin gravel bed at its base rests directly on the Pierre shale (see Plate 1, Fig. 2), the depth of erosion may have been still greater, but as the full section of the Titanotherium beds is not preserved there, it was impossible to measure the degree of erosion. The width of this valley was probably from 3 to 5 miles or more, for the "Interior" beds do not outcrop again until 8 or 10 miles to the south, in the lower parts of Corral, Quinn, and Battle Creek Draws. Figure 3 is a diagrammatic sketch of this valley cut in the "Interior" peneplain. The shape of this valley is hypothetical, but the left side of the diagram is based upon the sections measured in Indian Creek.

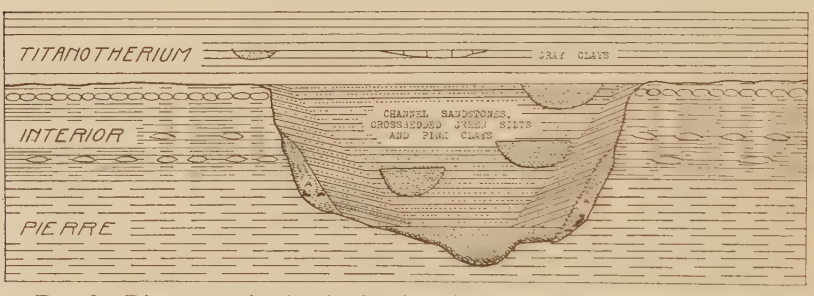



FIG. 3. Diagrammatic sketch showing the probable relations between the Pierre, "Interior," and Titanotherium beds, as observed on the North Branch of Indian Creek, 5 miles southwest of Scenic, based on Sections *G* and *H*. Vertical scale 60′ = 1″.

The preservation of Titanotherium bones at lower positions than Cretaceous marine fossils, as reported by Loomis,[11] might be possible along the sides of the valley where talus slopes or slumping of the "Interior" (Cretaceous) clays might bury occasional bones of Titanotheres or other White River animals (*A*, Fig. 3).

At the base of the Titanotherium beds deposited in the valleys eroded in the "Interior" peneplain is a gravel bed from three inches to a foot thick containing pebbles derived from the pre-Cambrian

[11] Op. cit.

section of the Black Hills. The pebbles of these gravels are larger in average size than those usually found in the channel deposits of the White River beds, but smaller in average size than the Pleistocene gravels described in a later section, usually being from one to three inches in diameter.

It was observed that the Titanotherium beds filling the valleys in the "Interior" peneplain are strongly colored in irregular bands, often resembling cross-bedding. The clays and finer silts are usually pink or red, while the coarser silts and sands are green. These pink clays and green silts are often steeply cross-bedded with observed slopes of 40° or more. These may represent the foreset beds of lateral delta terraces along the sides of the valley formed during its aggradation. Sometimes thin seams of fine gravel are observed between the bands of pink clay and green silt. The disappearance of the color banding as soon as the horizontal level of the old surface of the "Interior" beds is reached by channel filling and the extension of the Titanotherium clays as a cover over the "Interior" beds, protecting them from erosion, suggest that the coloring matter in the early Titanotherium beds was derived from the iron-stained "Interior" formation.

The initiation of erosion giving rise to the channels in which the lower Titanotherium sands were deposited must have been due either to uplift, a change of climate, or a combination of these factors. The Black Hills are believed by many geologists [12] to have been either completely submerged or nearly so during the time of the great Cordilleran sea of Cretaceous age. Cretaceous sediments are found with steep dips on the flanks of the Hills. If this was the case, the doming uplift with accompanying dissection must have taken place following the Cretaceous, for with the very beginning of Oligocene sedimentation (basal gravels of the Titanotherium beds) the granites, pegmatites, and schists of the pre-Cambrian core of the Hills were exposed to active erosion. It is probable that during the period of weathering resulting in the formation of the "Interior" beds the Black Hills were well mantled with vegetation and therefore not strongly eroded. Their altitude above the plain may have been less than at present, for

[12] Darton, "Geology of Southern Black Hills Region," U. S. G. S., 21st Ann. Rept., Vol. 4, 1900, pp. 556–558.

there has undoubtedly been marked uplift of the Hills since White River time.

After the formation of the "Interior" peneplain a climatic change involving greater aridity may have stripped the surface of most of its vegetation and allowed the surface soil to be removed more rapidly. With less soil and vegetation to hold the water, the rain, falling in cloudbursts and violent storms characteristic of an arid climate, may have run off rapidly and cut channels for itself in the soft shales of the "Interior" beds, thus rejuvenating the streams which had previously flowed across the surface of the plain in shallow channels. This dissection probably continued until the desiccation had also begun to affect the Black Hills. During this time a valley, or rather valleys, from one to several miles wide were formed, in which the rejuvenated streams flowed, but the period of erosion was evidently not long enough to smooth out the topography, as shown by the abruptness of the valley edge in Indian Creek, referred to above.

As the rock surface of the Black Hills became more exposed to erosion through the removal of soil and organic debris, the streams leading from this uplift out upon the plains carried a larger amount of clastic material, and soon this began to be deposited as sand and gravel in the stream beds. Thus the sandstones and conglomerate at the base of the White River had their origin. After the channel cutting, aggradation assumed a predominance over degradation in the area of the present Big Badlands which it retained throughout White River time. When the narrow central channel was filled, the streams spread sheets of silt over the valley floor, and occasionally shifted their channels. Lateral delta terraces, now represented by steep cross-bedding in the pink and green silts, formed along the sides of the valleys. This deposition of sandstones and pink and green silts continued until the valley had been completely filled and the old peneplained surface reformed as a plain of aggradation. Then the Titanotherium beds channels were free to wander over the plain at will and the uneroded portions of the "Interior" beds were preserved under a cover of gray Titanotherium clay.

*The Titanotherium Beds.*—The Titanotherium beds are distributed widely through western South Dakota and Nebraska, as well as

in northeastern Colorado and eastern and central Wyoming, but they have been studied by the writer only in the region of the Big Badlands of South Dakota. They have been described by Hatcher,[13] and their character in regions other than South Dakota, discussed by Matthew[14] for northeastern Colorado, Darton[15] for western Nebraska and eastern Wyoming, and Sinclair and Granger[16] for the Wind River and Big Horn basins. In the South Dakota Big Badlands the Titanotherium beds consist of spongy clay or silt, sandstones, conglomerates, and fresh-water limestones. All of these are subject to sharp lateral variation. The earlier writers held that the Titanotherium beds, as well as the other elements of the White River, were deposited on the bottoms of large lakes in quiet water. This view was supported by Hatcher in his paper on the Titanotherium beds, but was later abandoned[17] and a fluviatile hypothesis substituted. Fraas[18] believed that the Titanotherium beds were "deposited in a slow-moving river which emptied into a broad delta on level stretches of the Fort Pierre." He refers to conglomerate at the base of the Titanotherium beds.

It is more difficult to interpret the history of the Titanotherium beds than that of the later members of the White River because of their variability in thickness and lithologic character from point to point. Over large areas the whole of the Titanotherium beds is represented by spongy gray clays with occasional thin bands of limestone. In other areas sandstones and conglomerates from old stream deposits form a very prominent part of the section. It is in the latter that the remains of Titanotherium and other contemporary mammals are most commonly preserved. It is not usually possible to follow the courses of single channels clearly in the Titanotherium beds, although it appears that the general direction of flow was to the southeast or east. There were probably streams with shifting channels which frequently overflowed their banks and formed the widespread

[13] *Am. Nat.*, Vol. 27, 1893, pp. 204–221.

[14] *Mem. Am. Mus. Nat. Hist.*, Vol. 1, Pt. 7, 1901, p. 356.

[15] U. S. G. S., Prof. Paper 17, p. 40; Prof. Paper 32, pp. 169–175. Geol. Atlas, Folios 85, 88, 91, 173; 21st Ann. Rept., Vol. 4, 1900, pp. 542–545.

[16] *Am. Mus. Nat. Hist. Bull.*, Vol. XXX., pp. 83–117, 1911.

[17] *Am. Phil. Soc., Proc.*, Vol. 4, 1902, pp. 113–131.

[18] *Science*, N. S., Vol. 14, 1901, pp. 210–212.

clay deposits away from the channels. Channels were more numerous and a larger amount of coarse material was transported than in those cutting the Oreodon or Leptauchenia beds. The clastic material of the Titanotherium channel sandstones is mostly derived from the pre-Cambrian schists and pegmatites of the Black Hills, as noted by the writer in an earlier paper.

Another pronounced character of the Titanotherium beds is the abundance of fragments of fresh feldspar. This, in all samples studied, is predominantly microcline, and microcline is also the most abundant feldspar in the channel sands and gravels of all stages of the White River. Albite and oligoclase were rarely found, and orthoclase, when found, was more weathered than the other varieties. The gridiron structure of the microcline is usually very fresh. An interesting parallel to the White River channel sandstones is found in the Millstone grits of Yorkshire, described by Gilligan,[19] who states: "As with the larger pebbles, the dominant feldspar is microcline, next in order comes microcline-microperthite, then oligoclase, and orthoclase. Very basic feldspars appear to be altogether absent in the fresh state, and were never, I believe, present in any notable quantity. These feldspars are often exceedingly fresh. As in the larger pebbles, the cross-hatching of the microcline is wonderfully well shown, while the oligoclase is frequently quite unaltered. Microcline is, as is well known, the most resistant of all feldspars to alteration, and is found quite fresh in deposits of all ages."

Lenses of algal limestone, sometimes in the form of sheets and sometimes as levels of algal balls, all of which are local and generally very thin, from one to eight inches in thickness, are a common feature in the Titanotherium beds. At one locality in the basin of the north branch of Indian Creek algal balls were found which had grown around Unio shells. These were very abundant, forming a continuous sheet over an acre or so. At many places the limestones are irregularly replaced by silica in the form of opal or chalcedony. They were probably formed in shallow ponds on the surface of the flood plain in slight depressions where flood waters were undrained, the thinness of the limestone sheets indicating the temporary nature of these basins.

[19] *Quart. Jour. of Geol. Soc. of London*, Vol. LXXV., 1919, p. 262.

It is not evident whether the drainage of this region was carried through to an ocean basin at this time or not. The fact that the White River beds around Scenic have a larger number of channels than those near Interior, 30 miles farther from the Black Hills, suggests that the streams of White River time may have been distributaries spreading their deposits on a subaërial delta. Johnson [20] in describing the modern high plains points out that though the climate is not that of a desert and the region is not a structural basin, still "they have practically no drainage, the local precipitation being disposed of by absorption." The present is a period of erosion through the plains area as a whole, and the preservation of the high plains is partly due to a covering of sod, but during White River time the conditions favored aggradation rather than degradation, and it is quite reasonable to believe that the streams may have been distributaries from the points where they left the mountains until their disappearance by absorption and evaporation on the plain.

A fossil tree was found by the 1922 party almost at the base of the Titanotherium beds in the west branch of Corral Draw, with roots in the normal position of growth and sections of the trunk lying around near the stump. It has been submitted for study to Dr. R. W. Chaney, who reports that, from all the evidence at hand, it appears to be a *Celtis*.

As pointed out in the earlier paper, the Titanotherium clays are clearly differentiated from those of Oreodon age by a difference in their weathering characteristics. The slopes of the Titanotherium clay outcrops are rounded and deeply weathered. The writer, in endeavoring to obtain a fresh sample of this clay, dug into a bank to a depth of two or three feet, finding the clay below the surface quite damp, nearly saturated with water, and pale green in color. It is impossible to obtain a specimen of the clay which will not crumble to pieces on slight pressure of the hand. The amount of calcareous cementing material in the Titanotherium clays is distinctly less than that in the clays of the Oreodon beds, averaging only 1 to 5 per cent., while the Oreodon clays contain 10 to 30 per cent. The sharp change in the amount of cementing material at the contact seems to indicate that the cementation is not due to the activity of ground water after

[20] U. S. G. S., 21st Ann. Rept., Vol. 4, p. 610, 1900.

the deposition of the sediments. Therefore the change in the cement from Titanotherium to Oreodon clays indicates a change in the conditions of rainfall and surface water, and therefore a change in climate. The very discontinuous character of the clays and sandstone beds of Titanotherium age is also evidence of relatively humid climatic conditions.

According to Johnson,[21] "all streams carry rock material in solution, as well as a visible load in suspension, and commonly they are more or less 'hard' with dissolved calcium carbonate. But only desert streams deposit this chalky material upon their waste plains in appreciable quantity." The inference is that in a series of flood-plain clays those with a higher percentage of calcareous cement were deposited under more arid conditions than those with less calcareous cement, other factors such as the supply of calcium carbonate at the source remaining constant. Sheet flood action, when a flood from a river or a number of parallel rivers spreads over many miles of intervening flats, is also characteristic of semi-arid rather than of humid regions.

The conclusion to be drawn from the above facts with respect to the climate of Titanotherium time is that it was for the most part humid or semi-humid, and that the sediments were deposited in river channels and flood plains and as thin sheets spreading across the plain at times of torrential rainfall. The climate was seasonal, as the fossil tree found shows well-developed annual rings. Ponds were formed here and there on the surface of the plain in shallow depressions where the excess flood waters gathered and remained until evaporation or absorption had dried them up. In these ponds fresh-water algæ and some fresh-water mollusks flourished, at least while the water remained fresh. Probably the ponds were frozen over during the winter, at least occasionally, as the writer has several times found pebbles two or three inches in diameter embedded in the fine-grained calcareous deposits of the ponds. Ice seems to be the only agent capable of transporting such pebbles to the middle of a pond. There was probably a fairly rich cover of vegetation, though trees may have grown chiefly along the courses of streams. The *Titanotherium,* one of the largest land mammals of the earth's history, lived during this

[21] Ibid., p. 639 on.

period, and also, as Hatcher [22] pointed out, was undergoing rapid change toward its climax. The great size development of the Titanotheres may confirm other evidence presented above that the northern plains province during the period of deposition of the Titanotherium clays enjoyed a mild humid or sub-humid climate. It is a reasonable possibility that the extinction of the Titanotheres may have been brought about by a change to a period of less rainfall during Oreodon time.

On the other hand, the presence of gypsum in part of the Titanotherium beds shows that the favorable climate must have been interrupted by periods of marked aridity. It has not been observed by the writer, but is described as follows by Ward [23] for the Interior district: "One of the common variations is the presence of gypsum, which occurs only in the basal purple-red portion of the Titanotherium, but is found in many localities. There are no beds of this mineral. It occurs rather as irregular lumpy small masses usually only a few inches in diameter and with no alignment or evident plan or grouping. Occasionally several are connected. In some instances chalcedonic silica occurs with the gypsum, and, since on weathering, the gypsum is readily removed, the silica is at times found alone. A small amount of the gypsum is fibrous, occurring in narrow veins running in several directions with no well-established system." [23] Professor Fraas [24] mentions that "certain layers are very rich in gypsum and barite. Both minerals are now represented only in pseudomorphs of chalcedony, formed out of gypsum and barite." There are in several places large bell-shaped masses of chalcedony with hollow centers and botryoidal structure. These have been found up to a size of about one foot diameter. They are abundant in the lower Oreodon beds in Bear Creek basin about 5 miles south of Scenic. There are also frequent smaller concretions of chalcedony many of which Honess [25] has shown to be pseudomorphs after gypsum. He has also detected a little unreplaced gypsum. The writer has found a small nodule of tabular barite crystals in the badland

[22] *Am. Nat.*, Vol. 27, 1893, pp. 204–221.
[23] S. D. Geol. and Nat. Hist. Survey, Bull. 11, p. 22.
[24] Op. cit.
[25] *Amer. Jour. Sci.*, 4th Series, Vol. V., p. 173, February, 1923.

clays, and Honess detected barite crystals with calcite along the central unfilled portions of chalcedony veins, which are discussed below. Apparently the deposition of barite and gypsum took place throughout much of Titanotherium and Oreodon time, as the chalcedony pseudomorphs have quite a wide vertical distribution. They were probably desiccation products and it is observed that they are quite abundant in the lower red layer. Along the edge of Hart Table, 3 miles southwest of Scenic, a disconnected layer of chalcedony pseudomorphs was discovered, but they are usually found lying exposed on the surface, as they persist long after the removal of the clay by erosion. The gypsum may have been deposited in shallow playas during periods of unusual aridity in Titanotherium and Oreodon time.

The character and origin of the lower Titanotherium beds which were deposited in valleys cut into the peneplained surface of the Interior beds was fully discussed under the latter.

There are sandstone channels developed at various horizons within the Titanotherium beds, but it is rarely possible to follow a single channel for more than a quarter of a mile. The positions of two of these channels are shown in the sections in Fig. 2. In the valley of Indian Creek over quite a wide area a bed of channel sandstone from 15 to 25 feet in thickness rests directly on the Pierre shale surface. This is shown in Plate 1, Fig. 2. In Battle Creek draw over an area of several square miles are exposed uniform gray clays of the Titanotherium beds, with no channels and only occasional thin limestone lenses. In Corral Draw channels are numerous and at various levels, while at Interior no channels were observed, though Ward[26] in a detailed examination of the area found two small channel deposits in the Titanotherium beds.

Sandstone dikes and chalcedony veins occur throughout the Titanotherium beds, and will be treated separately in a later chapter.

*Titanotherium-Oreodon Unconformity and Limestone Sheet.*—Throughout the area of the Big Badlands and along the northern base of Pine Ridge, as described by Darton, there is a marked change in the character of the sediments at the contact between the Titano-

[26] Op. cit., pp. 21–22.

FIG. 1. Edge of Cooney Table, Battle Creek Draw, showing two algal limestone sheets ($a'$, $a''$) in the Oreodon beds. Marginal numbering corresponds with Text Fig. 5, section A1, and with Text Figs. 4 and 9A.

FIG. 2. Looking across Indian Creek, above its main forks from the level of the peneplain at the top of the Titanotherium beds. Contact of the latter with the Pierre shale is indicated by the pointers.

therium and Oreodon beds. In the Big Badlands the contact is slightly irregular. It is marked at many points by the presence of a thin discontinuous sheet of algal limestone from one to six inches thick. This thin limestone sheet was observed all the way from the Wall of the Badlands, north of Interior, to the head of Cedar Creek, about 65 miles to the southwest. Darton mentions the presence of a sheet of limestone at the top of the Chadron at Goshen Hole, Wyoming, on the North Platte River, about 150 miles from the Big Badlands, and in western Nebraska.[27] At some places it is absent and often it is almost completely replaced by silica either as chalcedony (brown or black) or as opal (white). This represents deposition in a shallow body of water, or rather many distinct shallow ponds. It contains fresh-water mollusks which are characteristic of small glacial ponds at present. Dr. Pillsbry[28] recognizes *Lymnæa,* two small species of *Planorbis,* an Ostracod of the nature of *Cypris,* and a well-preserved fish-scale, probably a small member of the *Cyprinidæ,* in material from this limestone at the base of the Wall of the Badlands five miles northeast of Imlay. He writes: "This appears to be a pond or shallow lake fauna. The snails are such as occur at the present time in the zone of abundant plants mainly less than 20 feet in depth. Very similar deposits are forming now in some ponds of the glaciated region of northern New Jersey, New York, and all the northern states. The great extension of the deposit . . . suggests widespread marsh and pond conditions. The lack of any land snails as well as the almost purely calcareous nature of the sediment excludes the idea of anything of the order of loess."

There is evidence of moderate erosion between the close of Titanotherium deposition and the algal limestone and Oreodon beds. This is indicated by the degree of irregularity in the contact surface. In Battle Creek Draw the contact drops 15 or 20 feet in level in a quarter of a mile and a thin sheet of algal limestone rests on the clay over the entire slope, showing that the period of limestone formation succeeded the erosion interval. The length of the time interval between Oreodon and Titanotherium beds deposition may only

[27] Geological Atlas of the U. S., Hartville Folio (No. 91), p. 3.

[28] Personal communication.

be conjectured, but the average thickness of Titanotherium clays removed during this interval apparently did not exceed 20 feet. A photograph reproduced in Sinclair's paper on the "Turtle-Oreodon Layer"[29] shows the Titanotherium-Oreodon unconformity very clearly along the edge of Hart Table, but the asterisk in the margin indicating the contact was unfortunately placed by the printer ¼ inch too high. The "rather persistent bed of reddish clay above which an Oreodon beds fauna occurs" at Interior,[30] at which the base of the Oreodon beds was temporarily placed when the Interior section was first studied by us in 1920, has not been recognized elsewhere in the badlands, and is now regarded as of no significance as a horizon marker.

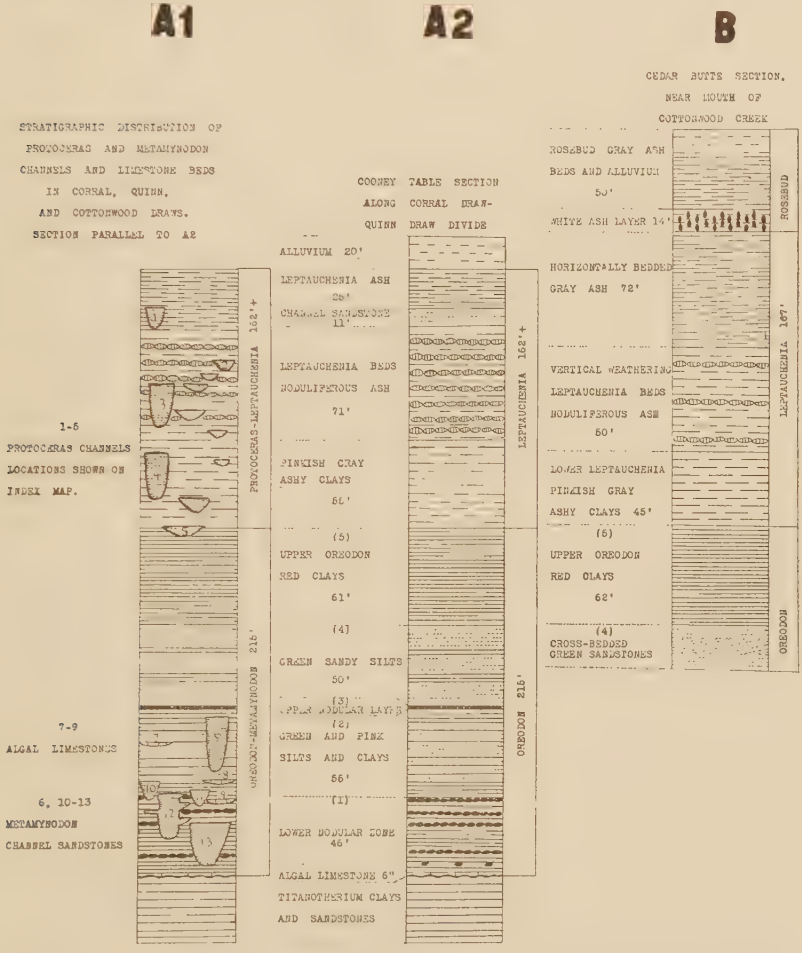
The climate of the time of deposition of the limestone must have been more humid than that at any other period of White River deposition in the area of the Big Badlands, because limestone sheets indicating fresh-water pond deposits were more widespread at this horizon than at any other. There is only a slight mixture of mechanical sediment in the limestone, though small fragments of quartz, biotite, tourmaline, and occasional glass fragments are found. These may have been blown into the pond as a dust.

This limestone sheet is more silicified in some areas than in others, and it was observed that where chalcedony veins were abundant the calcium carbonate was generally replaced by silica, while in areas where chalcedony veins are absent it remained a limestone, often containing only 4 or 5 per cent. of non-calcareous material. This suggests that the silicification was due rather to ground water than to diatoms or other siliceous organisms in the limestone, and that the distribution of silica-rich ground water was irregular rather than universal.

*The Oreodon Beds.*—The Oreodon beds are widely developed and exposed throughout the western part of the Great Plains province, especially in northeastern Colorado, where they are called the Cedar Creek beds by Matthew; in southeastern Wyoming; and in western Nebraska and South Dakota. Their characters in regions outside the

[29] Proc. of Amer. Phil. Soc., Vol. LX., 1921, Plate VII., Fig. 1.
[30] Ibid., p. 459.

Big Badlands are described by Matthew,[31] Darton,[32] and Todd.[33] Osborn [34] and Matthew [35] have discussed and listed the mammalian fauna, which is one of the largest known from the Tertiary formations of the west.


A1
A2
B
STRATIGRAPHIC DISTRIBUTION OF PROTOCERAS AND METAMYNODON CHANNELS AND LIMESTONE BEDS IN CORRAL, QUINN, AND COTTONWOOD DRAWS. SECTION PARALLEL TO A2
1-5 PROTOCERAS CHANNELS LOCATIONS SHOWN ON INDEX MAP.
7-9 ALGAL LIMESTONES
6, 10-13 METAMYNODON CHANNEL SANDSTONES
PROTOCERAS-LEPTAUCHENIA 162'+
OREODON-METAMYNODON 216'
COONEY TABLE SECTION ALONG CORRAL DRAW-QUINN DRAW DIVIDE
ALLUVIUM 20'
LEPTAUCHENIA ASH 25'
CHANNEL SANDSTONE 11'
LEPTAUCHENIA BEDS NODULIFEROUS ASH 71'
PINKISH GRAY ASHY CLAYS 56'
(5) UPPER OREODON RED CLAYS 61'
(4) GREEN SANDY SILTS 50'
(3) UPPER NODULAR LAYER
(2) GREEN AND PINK SILTS AND CLAYS 56'
(1) LOWER NODULAR ZONE 46'
ALGAL LIMESTONE 6"
TITANOTHERIUM CLAYS AND SANDSTONES
LEPTAUCHENIA 162'+
OREODON 216'
CEDAR BUTTE SECTION, NEAR MOUTH OF COTTONWOOD CREEK
ROSEBUD GRAY ASH BEDS AND ALLUVIUM 50'
WHITE ASH LAYER 14'
HORIZONTALLY BEDDED GRAY ASH 72'
VERTICAL WEATHERING
LEPTAUCHENIA BEDS NODULIFEROUS ASH 50'
LOWER LEPTAUCHENIA PINKISH GRAY ASHY CLAYS 45'
(6) UPPER OREODON RED CLAYS 62'
(4) CROSS-BEDDED GREEN SANDSTONES
ROSEBUD
LEPTAUCHENIA 167'
OREODON

FIGS. 5–6. Parallel columnar sections of the Oreodon, Leptauchenia, and Lower Rosebud beds in the Big Badlands. (*A*–*E* on the map, Fig. 1.) Vertical scale 120′ = 1″. Shape of channels in Section $A_1$ conventionalized.

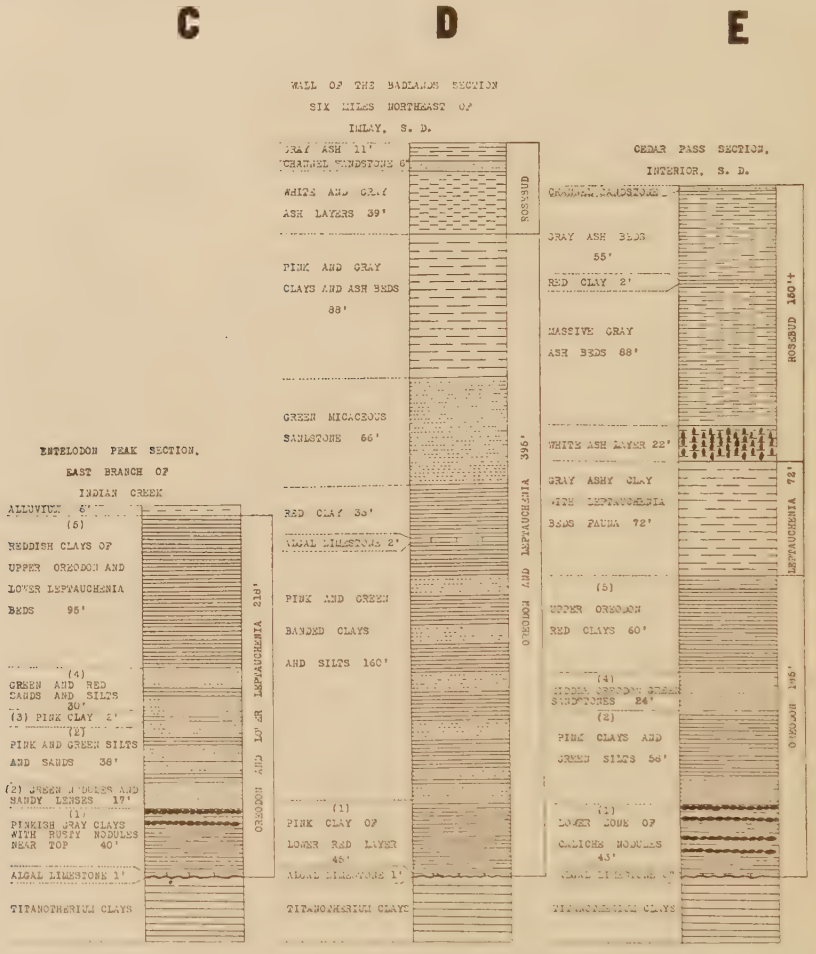
[31] *Mem. Am. Mus. Nat. Hist.*, Vol. 1, Pt. 7, 1901, p. 356. N.E. Colorado.

[32] U. S. G. S. Prof. Paper 17, pp. 38–40; Prof. Paper 32, pp. 169–175; Geol. Atlas, Folios 85, 87, 88, 91, 173; 21st Ann. Rept., Vol. 4, 1900, pp. 542–545.

[33] S. D. Geol. Surv., Bull. No. 2, 1898, pp. 43–68.

[34] U. S. G. S., Bull. 361, pp. 62–63.

As most of the collections made by the Princeton expeditions have come from the two zones of caliche nodules in the lower part of the Oreodon beds, this series has been more widely observed by the writer than any other member of the White River formation.




In Figs. 5 and 6, five columnar sections of the Oreodon beds and parts of the overlying Leptauchenia beds are represented. These sections are distributed as follows (see Index map, Fig. 1): (*A*) at

[35] Ibid., pp. 105–6, 110–11.

the head of Corral Draw to the top of Cooney Table at the divide between Corral, Quinn, and Cottonwood Draws; (*B*) at the Cedar Butte, a high isolated butte about 2 miles northwest of the junction of Cottonwood Creek and White River and about 10 miles south of Sheep Mountain; (*C*) at Entelodon Peak, named by the Princeton party in 1920 because of the numerous skulls and jaws of entelodonts collected in the vicinity of this butte in the lower zone of caliche nodules, near the head of the east branch of Indian Creek, and about 6 miles southwest of Scenic; (*D*) at the western end of the Wall of the Badlands from the valley level to the top of a conspicuous high flat-topped butte capped by a massive layer of channel sandstone—this is 5 or 6 miles northeast of Imlay station; (*E*) the Cedar Pass section of the Wall of the Badlands, about three miles northeast of Interior. The discussion of the Oreodon beds will be based on these sections, as they are quite widely distributed through the area.

The Oreodon beds will, for convenience, be divided into five elements, each of which has sufficiently distinct character and wide lateral extent to entitle it to separate consideration. The divisions are shown in Fig. 4.

(1) *The Lower Nodular or Caliche Zone.*—This is one of the most uniform and widely distributed horizons of the western Tertiaries. It extends with comparatively little change in thickness or lithologic character from the eastern part of the Wall of the Badlands, west and southwest to the head of Cedar Creek, the farthest point in that direction reached by the Princeton parties, and Professor Loomis has informed the writer that it is similarly developed in the Hat Creek basin in northwestern Nebraska and eastern Wyoming, a distance of 150 miles from the Interior section.

It consists of fine silt generally colored a pale pink and when weathered a light rusty brown. It contains fragments of quartz, biotite, muscovite, tourmaline, and more or less weathered feldspar, with a small amount of volcanic glass, which never, however, forms an important constituent of the silt. It has from 10 to 15 per cent. of calcareous cement, and where consolidated into caliche nodules may contain from 25 to 30 per cent.

The lower red layer varies as follows in the section shown: Corral Draw, 46 feet; Indian Creek, 40 feet; northeast of Imlay, 45 feet; and the Cedar Pass section, 43 feet. It is not exposed in the Cedar Butte section in Cottonwood Creek. This is a degree of regularity extremely unusual in continental deposits.

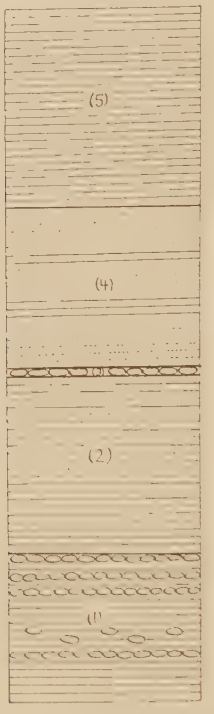



Fig. 4. Divisions of the Oreodon beds recognized in the sections in the Big Badlands. Vertical scale 60′ = 1″.

The nodules are developed along certain definite levels throughout the zone. These levels are generally more abundant toward the top of the red layer. In Indian Creek around Entelodon Peak three levels of nodules occur, all in the upper 6 or 7 feet of the zone. In Corral Draw nodules are developed throughout the red layer at frequent levels to within a foot or so of its base. In Battle Creek Draw nodules are generally absent, and are found only in the vicinity of one or two small channel sandstone deposits. In some sections northeast of Scenic in Sage Creek and Cain Creek basins, and the section

of the Wall of the Badlands northeast of Imlay, no nodules are found, but the total thickness of the red layer is represented by a uniform series of pinkish clays. At Interior caliche nodules are again well developed.

Ward [36] describes the section of the Oreodon beds at Interior and states that there are from 115–135 feet of banded red and green silts of Lower Oreodon age below the Lower Nodular layer. It is not possible to identify all of his field divisions with the writer's section at Interior. He describes an unconformity at the base of the Oreodon beds, and states that in one instance the unconformity was angular with an angle as high as twelve degrees. The beds below the lower red layer in the Interior section have not been carefully studied by the writer. As noted above, at many widely separated localities throughout the Big Badlands the lower red layer was found to vary in thickness between 40 and 46 feet. It always rested upon the Titanotherium beds unconformably, and generally was separated from the latter by a band of fresh-water limestone less than a foot in thickness. Therefore, when the section of the lower red layer at Interior was found to measure 43 feet, a thickness intermediate between the maximum and minimum observed elsewhere in the Big Badlands, and a thin band of algal limestone was observed at its base (on the ranch of W. E. Brown, about 2 miles northeast of Interior), it was assumed by analogy that the beds below this level were of Titanotherium age. No titanotheres were observed in these beds immediately below the Lower Red layer, and therefore the writer has no faunal data for this correlation. The difference between the writer's Interior section and Ward's may be due to (1) a different use of the term Lower Nodular layer; (2) an erosional break within the Titanotherium beds which Dr. Ward has interpreted as the Titanotherium-Oreodon contact; or (3) a great thickening of the Lower Oreodon beds whereby 115 to 135 feet were deposited during the period represented by the Titanotherium-Oreodon gap in the Big Badlands. The latter assumption seems unlikely, inasmuch as the Red layer with a thickness of 45 feet rests upon normal Titanotherium clays in the section of the Wall of the Badlands northeast

[36] Op. cit., pp. 24–26.

of Imlay (*D*) only 20 miles west of this locality. This correlation could probably be settled satisfactorily by observations along the base of the Wall of the Badlands between Imlay and Interior where the lower Oreodon beds are continuously exposed.

The writer's interpretation of the formation of caliche nodules, as outlined in the earlier paper [37] and by Sinclair,[38] is that each horizon of caliche nodules represents an old land surface under conditions suitable for high evaporation. This would probably be a warm and semi-arid climate. The clay at or near the surface of the plain was then cemented by calcareous material, which was deposited by the ground water as it evaporated. Pilgrim [39] describes similar concretionary pseudo-conglomerates which characterize the Lower Siwaliks of Northern India. He suggests two possible origins for them: "(1) formation beneath water, due to segregation of calcareous material implying contemporaneous origin, and (2) formation subsequent to deposition. If the latter is accepted, there are two alternatives: (1) Formation at a much later date in the nature of veins and pockets produced by infiltration. This would not account for thin bands widely distributed and should be absent from adjacent sandstones and clays. (2) The entire concretionary structure of a particular band was produced in it before the deposition of layers above it. The only way in which this can have taken place would be if long periods of entire or almost entire cessation of flood alternated with periods during which floods were of constant, probably annual occurrence. During periods of rest large portions of land surface must have remained almost dry and have been subjected to atmospheric forces, capillarity and evaporation, such as determine the formation of kankar in the plains of Bengal at the present day. The concretionary band, therefore, represents a soil layer, which is of greater or lesser thickness, according to whether it has remained subject to atmospheric influences for a longer or shorter time. Since it may be concluded that the layers of sediment left exposed during each of the periods of desiccation would vary in their lithological

[37] Proc. Amer. Philos. Soc., Vol. LXI., 1922, pp. 195–197.
[38] Proc. Amer. Philos. Soc., Vol. LX., 1921, pp. 462–465.
[39] Records of Geol. Survey of India, Vol. XLII., Pt. 4, 1913.

character, being sometimes sand and sometimes clay, we should expect the subsequent character of the concretionary band to vary also. This is in fact the case. The color and material of the matrix is very different in different bands, although the nature of the concretionary action in general appears to have been the same." [40] He goes on to suggest that the great frequency of concretionary layers in the Lower Siwaliks, implying numerous halts in deposition, may mean that twice as much time is demanded for their deposition as for that of the Middle Siwaliks in which there is not much evidence of halts in deposition. A close parallel to the caliche layers in the White River formation is here presented and an explanation almost identical with that adopted for South Dakota conditions has been reached. Pilgrim's suggestion of the lengthening of the total period of deposition is important, and may imply a length of time out of proportion to their thickness for the Lower Oreodon beds.

The irregularity of the development of the caliche nodules both in the Oreodon beds and the Leptauchenia beds presently to be mentioned is a problem for solution. As mentioned above, over wide areas such as most of the basin of Cain Creek northeast of Scenic nodules are practically absent in the Red layer, the total thickness being represented by pink clay. There are no channel sandstones observed in the Lower Oreodon beds in this area. Near the head of Battle Creek Canyon southwest of Scenic, after prospecting several miles of exposures of the Red layer where nodules were not developed, a small area with a rich exposure of caliche nodules was found. Within a hundred yards of this outcrop was the only stream channel which had been seen in the Lower Oreodon beds in this whole creek basin. The very rich development of caliche ash nodules around the Protoceras channels at the head of Corral Draw (described below) and their absence elsewhere in the Leptauchenia beds also suggests a connection between stream channels and caliche nodule development. It is probable that the absence of caliche nodules away from the stream channels is due to the fact that the water table is further from the surface, and therefore the evaporation of water drawn to the sur-

[40] Ibid.

face by capillarity and the deposition of $CaCO_3$ as a cement of the clays is correspondingly less. The caliche beds are only well developed in the vicinity (within a quarter to half a mile) of the courses of the old stream channels where the amount of ground water and its dissolved carbonates would be greater.

It has recently been observed that most of the clays of the Lower Oreodon beds, as well as the caliche nodules, are composed of small rounded balls or pellets of clay varying from the size of wheat grains to that of a large hickory nut. These are enclosed in a matrix of clay usually slightly different in color. They evidently are formed of small fragments derived from the land surface of the bed below, plucked by advancing flood waters and incorporated in the silts deposited by the flood upon its subsiding. The rounded form of the pellets is evidently due to the rolling and may have resulted in some rounding off of angular faces and accretion of clay picked up while the pellets were moving. As these do not show a concentric development, the latter does not seem to have been as important a factor as the former. The pellets may be easily detected by the unaided eye and sometimes weather out as hard rounded balls about the size of hickory nuts.

Plate III., Fig. 2, shows such a pellet conglomerate from the Lower Nodular layer in Battle Creek Draw. Clay balls are found in the bottom of many badland draws today. These are of much larger size and somewhat different origin. They average from 5 inches to a foot in diameter and are formed mainly by accretion. Extraneous material, such as fragments of chalcedony veins and small pebbles, are found in these masses as well as clay. They may be easily broken up by slight pressure. There is an excellent illustration of these modern clay balls in Dr. O'Harra's Badland report.[41] The presence of clay balls abundantly distributed through the badland clays is one of the most definite proofs of the sheet-flood transportation of the clays containing them, for the settlement of finely divided clay in lake basins does not produce these structures.

It may be well here to review a few of the other evidences found in the zones of caliche nodules in support of the flood-plain deposition

[41] S. D. School of Mines, Bull. No. 13, Plate 71*A*.

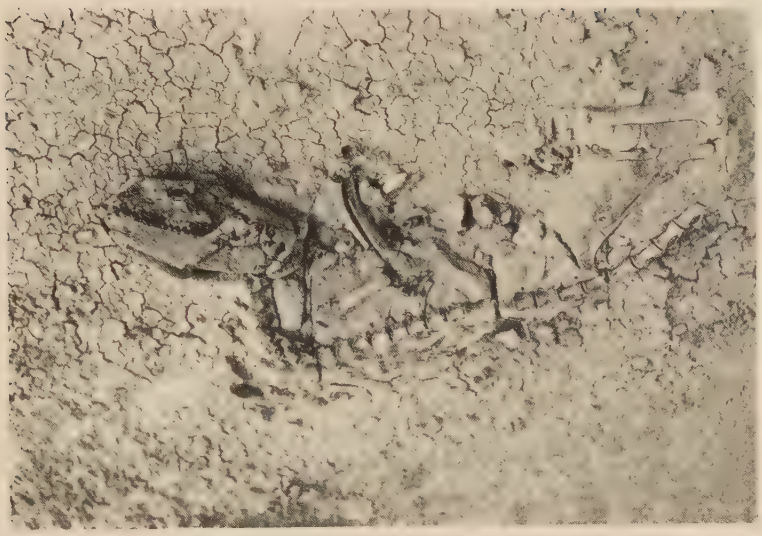


FIG. 1. Articulated skeleton of *Oreodon culbertsoni periculorum* in death pose. Lower concretionary zone, Oreodon beds, Bear Creek basin.

FIG. 2. Clay pellet conglomerate from the Lower Nodular layer in Battle Creek Draw. Part of a large nodule inclosing two individuals of the sabre-tooth tiger *Hoplophoneus primævus*. No magnification.

FIG. 1. Upper Nodular layer, Oreodon beds, Corral Draw basin, about one mile southwest of Cottonwood Pass.

FIG. 2. Lower Nodular layer, Oreodon beds, in Indian Creek basin near the Big Corral Draw divide.

FIG. 1. In Corral Draw, south of Cottonwood Pass. Section of the Oreodon beds numbered to correspond with A1 and A2, Text Fig. 5, and also with Text Figs. 4 and 9A.

FIG. 2. Main head branch of Corral Draw cutting a Metamynodon channel (No. 12, Text Figs. 5A1 and 7). Protoceras channel to right of central butte.

of the sediments. Sinclair[42] has discussed some of these in an earlier paper.

(1) Turtles are very abundant in the red layer. Frequently the fossilized carapaces are found in all sorts of positions (bottom side up, or even on edge), and the hollow central cavities are filled with clay usually containing small clay pellets of the type above described. These turtles are all land tortoises, mostly of the species *Stylemys nebrascensis*. The only aquatic turtles collected from the badlands are from the stream channels.

(2) It was mentioned above in connection with algal pond deposits that fresh-water gastropods were found abundantly in the limestones of pond origin through the Oreodon and Titanotherium beds. In the upper and lower red Oreodon clays, and the Leptauchenia nodular clays at Interior, land snails have been found fossilized in caliche nodules. These have been specifically determined by Dr. Pillsbry as follows: *Helix leidyi* (Meek and Hayden)[43] a land snail, in the Lower Red layer and Leptauchenia clays, and *Lymnæa shumardi* (Meek and Hayden) probably a fresh-water gastropod, in the upper read clays.

(3) Mouse-gnawed bones are frequently found in the badland clays.

(4) In the preparation of a *Cœnopus* skull many casts of insect larval burrows were found within and around the skull, suggesting that it had lain on the surface for some time before burial, and the flesh had been devoured by the scavenging insects which subsequently burrowed for pupation in the mud investing the skull. Similar larval burrows are found isolated in the clays and not associated with skulls or other bones.

(5) Coprolites of carnivorous animals are abundantly preserved in the badland clays. They are specially numerous around skulls or partial skeletons of herbivorous animals such as *Oreodons* and *Entelodons*, but do not represent the intestinal contents of these animals, since they often show fragments of bone. Many of the coprolites have not been softened and show distinctly the impress of the anal muscles. It is known that modern carnivores have a habit of sniffing

[42] Proc. of Amer. Phil. Soc., Vol. LX., 1921, pp. 461–462.

[43] U. S. Geol. Surv. of Territories, Vol. IX., Meek, pp. 598–604.

around inedible substances and defecating disgustedly thereon. Hatcher, collecting in the western badlands, once had the experience of having several packages of fossils torn open by a coyote in his absence, and fecal material dropped on each package.

(6) At many places throughout the outcrops of the nodular layer fragmentary remains of several different kinds of animals are found close together, often within an area ten feet or less in diameter. For example, in the valley of the north branch of Indian Creek skull and jaw fragments of *Hoplophoneus, Hyænodon, Oreodon, Leptomeryx, Perchœrus,* and *Mesohippus* were all found close together. These bone piles probably were accumulated by being dragged to their present positions by carnivorous animals. In the locality referred to there may have been the lair of some Oligocene sabre-toothed tiger or *Hyænodon.*

(7) Occasionally skeletons are exposed on the plain in death pose. "In 1920 an articulated *Oreodon* skeleton collected by the Princeton expedition had the head and neck bent back in a manner frequently observable in the more or less dried-up carcasses of sheep killed in storms."[44] This skeleton is shown in Plate III., Fig. 1.

(8) In 1922, in Battle Creek Draw, two skeletons of sabre-toothed tigers (*Hoplophoneus*) were found in the Lower Red layer in Battle Creek Draw in a very restricted area, about one yard in diameter. No sabres were found in the skulls, but all four of the sabres were found separately associated with toe bones, vertebræ, and other skeletal parts. These skeletons were probably embedded in some local depression.

(9) Articulated skulls and jaws of Oreodons detached from any other skeletal remains are very common in the badland clays. These heads may have been dragged off by carnivorous animals from the remainder of the skeleton. A large enteledont skull collected in Indian Creek (Entelodon Peak) in 1920 had the cervical vertebræ in articulation, and a few other fragments of bones were found in the vicinity, but none of the large limb bones of the entelodont were visible. This would hardly have been the case if the head had not been moved away from the carcass, as the limb bones of a large entelodont are massive and would almost certainly be preserved.

[44] Sinclair, op. cit., p. 462.

The above facts observed in the field can all be easily interpreted by assuming a level plain subject to periodic flooding, but are very hard to explain if the deposition is held to be lacustrine.

(2) *Lower Oreodon Banded Silts.*—Division (2) of the Oreodon beds includes a sequence of banded pink and green silts. In some sections, as in Battle Creek Draw, the green beds predominate and are locally quite sandy. In the section in Corral Draw greenish or grayish silts predominate, but there are several thin bands of reddish clay running through it. This division is not exposed at the Cedar Butte near the mouth of Cottonwood Creek (Section B), and its upper limit is not differentiated in the section northeast of Imlay, as the Upper Nodular layer which ordinarily bounds it above is absent there. Its thickness is 55 feet in Corral Draw and Indian Creek and 58 feet at the Cedar Pass section near Interior. Plate V., Fig. 1, shows the development of this zone in Corral Draw, near Cottonwood Pass. Caliche nodules are absent from this division, though the greenish silt beds often weather in rounded forms, resembling the caliche nodules in size and shape. In Bear Creek basin, five miles south of Scenic, two or three beds of these greenish silt nodules occur just above the upper limit of the Lower zone of caliche nodules.

*Metamynodon Channel Sandstones.*—Here and there throughout the Big Badlands lens-shaped masses of sandstone and conglomerate, characterized by the presence of the large aquatic rhinoceros *Metamynodon,* cut the normal sequence of clays and caliche nodules in the Lower Oreodon beds (Pl. V., Fig. 2). These channels are sometimes represented only by small masses of fine-grained micaceous sandstone, as in the north branch of Indian Creek, adjacent to Hart Table, while in the upper part of Corral Draw, Cottonwood Creek, Indian Creek, and Quinn Draw these channels occur more frequently than elsewhere in the badlands and are represented by thicker and coarser sandstones. Here they commonly consist of alternations of coarse conglomeratic beds with finer micaceous sandstones, which can often be followed for a mile or more. As the sandstones are much harder rocks than the adjacent clays, their massive conglomeratic beds stand up from 15 to 50 feet above the levels of the adjacent creek valleys. The columnar section *A*1, Fig. 5, shows the stratigraphic positions of some

of these channels in the Lower Oreodon beds, and Fig. 1 shows the geographical distribution of some of the lenses of channel sandstone in the Corral Draw area. It will be observed that the channels are cut both in the Lower Nodular zone and in the clays above it, but more abundantly in the latter. If a channel sandstone dies out laterally at a level at which caliche nodules are developed, these are locally absent for 100 to 200 feet on either side of the channel. However, in some cases a channel cuts a level of nodules formed at an earlier time than the channel. Then the nodules may be developed to the very edge of the channel, where they terminate abruptly against the sandstone.

The channels vary considerably in width. Channel No. 13 of Sec. *A*1, Fig. 5, is about 100 yards in average width and has cut down nearly into the Titanotherium beds, while Channel No. 11 is narrow and less than 50 feet in average width. These channels probably represent braided streams in which one main river was divided into several narrow channels by frequent islands. In one section in Indian Creek and two in Corral Draw the channels have been observed to pass laterally into algal limestones or to rest on algal deposits. Sinclair [45] has described this phenomenon in Indian Creek. The mineral composition of the Metamynodon channels was discussed by the writer in the earlier paper, and no new data have been accumulated.

Algal limestone deposits occur more frequently in Division (*2*) than elsewhere in the Oreodon beds with the exception of the discontinuous sheet at their basal contact. Section *A*1, Fig. 5, shows the vertical distribution of the algal beds in the Corral-Quinn-Battle Creek Draw area, and Fig. 7 shows the geographical locations of the ponds in which they were formed. In Plate II., Fig. 1, a portion of the edge of Cooney Table in Battle Creek Draw is seen with two limestone beds between the Upper nodular layer and the Lower zone of caliche nodules. They are 20 and 40 feet, respectively, below the Upper nodular layer. An algal pond deposit (No. 9 in Fig. 1 and Sec. *A*1) near the Corral-Indian Creek divide 1 mile northeast of Cottonwood Pass is just below the top of the Red layer. The lower limestone bed shown in the photograph is very local (not over 100

[45] Op. cit., pp. 460–461.

yards in diameter), but the upper limestone bed is persistent as a thin algal-ball level over several square miles on the southern side of Quinn Draw basin, where it usually forms a pronounced bench. The

FIG. 7. Sketch map of a portion of the basins of Battle Creek, Quinn, and Big Corral Draws, Indian Creek, and Cottonwood Creek, in the Big Badlands, showing the distribution of Metamynodon and Protoceras channel sandstones, and algal limestone pond deposits in the Lower Oreodon beds. Adapted from map of the Pine Ridge Indian Reservation (Dept. of the Interior, Office of Indian Affairs, 1914). Scale 1/42240. (3 miles = 2″.)

algal balls are flattened oval-shaped and about 6 inches in length and 2 to 4 inches in thickness. In these are found abundant fresh-water pond invertebrates, especially *Planorbis* and Cyprid crustaceans. They sometimes have hollow centers and generally a concentric structure. Sometimes the growth started around a clay pellet or mammalian tooth or bone, or (as in the Titanotherium beds in the north branch of Indian Creek) around a *Unio* shell, and continued outward growth until the drying up of the pond. The algal-ball levels may represent shallow ponds or damp meadows of shorter duration than

those which have formed a solid sheet of limestone. The fauna seems to have been essentially the same.

(3) *The Upper Nodular Layer.*—This is a single horizon of caliche nodules which is very widespread in the Big Badlands. It is developed from the vicinity of Arnold's ranch (see map, Fig. 1) on the east, westward about 30 miles to the headwaters of Cedar Creek, the farthest point to the west reached by the Princeton expeditions. Where nodules are not present at this horizon it is usually represented by a band of pinkish clay. This is the case in the Entelodon Peak section and adjacent portions of Indian Creek. It has not been recognized in the Bear Creek sections east of Scenic, nor at Interior, but is an excellent horizon marker throughout the Corral-Quinn-Cottonwood-Battle Creek Draw area. Plate IV., Fig. 1, illustrates a fine development of nodules at this horizon in Corral Draw basin about one mile southwest of Cottonwood Pass. These nodules contain quite abundant vertebrate remains, as do those of the Lower zone of caliche nodules. Osborn and Wortman,[46] speaking of *Oreodon bullatus,* state: "There is a single skull in our collection which was obtained from the second nodular layer, from 75 to 100 feet above the 'Red Layer' of the 'Oreodon bed.'" This is evidently a reference to the Upper Nodular layer as here defined. Interruptions of the Upper Nodular layer by channels or algal limestones have not been observed, and doubtless it represents a short recurrence of semi-arid climate similar to that prevailing during the deposition of the lower zone of caliche nodules. The average thickness of this layer is about one foot. Above it two feet of gray unconsolidated clay resembling the spongy Titanotherium clays usually are found, then the green sandy silts of division (4) of the Oreodon beds.

(4) *Middle Oreodon Green Sandstones.*—This division is characterized throughout the Big Badlands by a green or gray-green color, and unusually sandy nature. It is at the base of the section at the Cedar Butte (Sec. *B,* Fig. 5) and there and in the valleys of Battle Creek Draw and Battle Creek Canyon to the west is a massive green sandstone. Plate I., Fig. 1, shows well the development of this zone along the edge of Cooney Table in Battle Creek Draw. Its thickness

[46] *Bull. Amer. Mus. Nat. Hist.,* 1894, Vol. VI., p. 218.

in Corral Draw is 55 feet (Sec. *A2*), while at Interior it is represented by 24 feet of greenish silts (Sec. *E*). Although these form continuous beds of sandstone, they often weather into rounded forms resembling in shape and size the caliche nodules, hence Ward [47] describes this bed as the Upper Nodular sandstone, and the writer in the earlier paper [48] referred to it as the Upper zone of nodules, more generally green than rusty. Fossils are rarely observed in this division, although turtles and fragmentary mammalian remains are occasionally found.

(5) *Upper Oreodon Red Clays.*—Above the zone of greenish sands and silts (4) there is almost always an abrupt change of phase to a red clay resembling in character that of the Lower Red layer where nodules are not developed in it. Microscopic examination shows that it differs from the Lower Oreodon clays in having a notably higher content of volcanic glass and pumice fragments. It is generally exposed in steep walls, as the Leptauchenia beds overlying are usually more resistant to weathering than this division. Plate I., Fig. 1, shows clearly the change from divisions (4) to (5) in the Battle Creek Draw section, as well as the light-colored band which at present is used to define the contact between the Oreodon and Leptauchenia beds. This division of the Oreodon beds has a thickness of 62 feet at the Cedar Butte in Cottonwood Creek, 61 feet at the head of Corral Draw, and 60 feet at the Cedar Pass section near Interior, another remarkable example of uniformity over wide areas. In the Entelodon Peak section the upper limit of this division is not defined, and the 95 feet at the top of the section probably include part of the lower division of the Leptauchenia beds. In the section at the head of Corral Draw the lowest Protoceras channels cut down into this division about 10 or 15 feet.

The section of the Wall of the Badlands, northeast of Imlay, can not be clearly interpreted. The visit made here was brief and the only divisions clearly correlated with the other exposures of the Oreodon and Leptauchenia beds were the Lower Nodular layer and the White Ash (defined below). The beds between were all alternations of pink and green silts, with one bed of massive sandstone 66

[47] Op. cit., pp. 27–28.

[48] Proc. of Amer. Philos. Soc., Vol. LXI., 1922, p. 187.

feet thick, at a position corresponding to the upper red clays of the Oreodon beds. The relations of this section to others of the White River formations could be worked out by more detailed study, but the section is presented here principally to show the persistence of the limestone at the base of the Oreodon beds, the Lower Red layer, and the White Ash.

*The Leptauchenia-Protoceras Beds.*—The Leptauchenia beds are less widely recognized in the Great Plains region than are the underlying Oreodon beds. They are included with the Oreodon beds in the Brulé clays of Darton.[49] Matthew recognizes them in northeastern Colorado, and names them the lower "Martin Canyon" beds.[50] Osborn [51] gives the correlation and distinctive faunal characteristics of the deposits of this age and Matthew [52] has published a list of the known fauna from this zone.

The Leptauchenia beds in the Big Badlands may be clearly separated into three divisions, but these divisions have not yet been recognized in the Interior section at Cedar Pass. It is very difficult to decide where the base of the Leptauchenia beds should be drawn, as there is no sudden change in the lithologic character of the sediments such as that which initiates Oreodon beds deposition. As the Leptauchenia-Protoceras zone is a faunal division, the contact has been tentatively placed by the writer at the level along which the lowest channel with a *Protoceras* and *Leptauchenia* fauna dies out laterally. This is a light-weathering band which can easily be traced for many miles in the Big Badlands. This plane of division differs from that in the section published in the previous paper in that it transfers to the Lower Leptauchenia beds 50 feet of reddish clays there included in the Oreodon division. The channel which is situated lowest stratigraphically had not been seen when the section published last year was measured, and there was then no reason for believing that the Protoceras-Leptauchenia fauna extended lower than the level of the lowest observed channel carrying this fauna.

[49] U. S. G. S., Prof. Paper 32, pp. 170–175.
[50] *Mem. Am. Mus. Nat. Hist.*, Vol. 1, Pt. 7, 1901, pp. 353–447.
[51] U. S. G. S., Bull. 361, pp. 53–64.
[52] Ibid., pp. 106–111.

The relations between these sections as now revised is shown diagrammatically in Fig. 8.

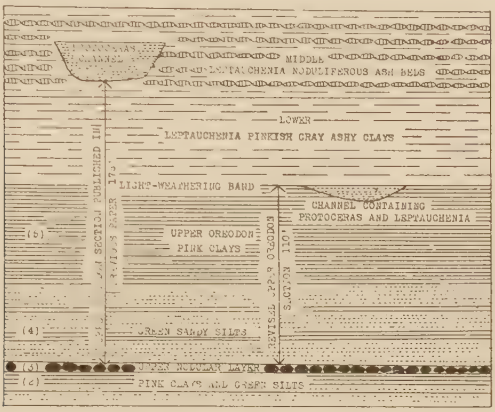



FIG. 8. Sketch showing the revision of the section of the Upper Oreodon beds and the stratigraphic position of the Leptauchenia-Oreodon contact at the head of Big Corral Draw, Big Badlands. Vertical scale 120′ = 1″.

*Division (1).*—The lowest division of the Leptauchenia beds in the Big Badlands is a reddish or gray clay with a considerable amount of volcanic glass and pumice fragments. This does not differ notably in its type of weathering from the upper division of the Oreodon beds (5) as here defined. The plane of contact with the Oreodon clays, as mentioned above, is a light-weathering band which is clearly recognizable over a large portion of the Big Badlands, and is plainly visible in the accompanying photograph, Plate I., Fig. 1, a section of the edge of Cooney Table in Battle Creek Draw. The lowest Protoceras channel dies out laterally at this level and cuts 25 feet below it into the clays of the Upper Oreodon beds. The thickness of this lower division of the Leptauchenia beds is 45 feet in the Cedar Butte section and 55 feet in the Cooney Table section, Corral Draw.

*Division (2).*—The middle division of the Leptauchenia is best exposed along the divide between Big Corral Draw and Cottonwood Creek in the Big Badlands and along the adjacent edge of Cooney Table. It is characterized by the development of levels of caliche nodules resembling in appearance those of the Lower Oreodon beds, but not containing mud pellets. Analysis of one of the caliche nodules

showed it to contain 38 per cent. of calcareous cementing material. The silt consisted mainly of quartz, volcanic glass, and biotite, the glass amounting to 50 per cent. or more of the total. The stream channels (Pl. VI., Figs. 1 and 2) carrying a *Protoceras* fauna are very abundant in this division of the Leptauchenia beds and are found at a variety of levels, often initiated by a coarse conglomeratic sandstone, followed by a fine-grained green micaceous sandstone, and capped by another ledge of coarse massive sandstone. The caliche nodules are developed most strongly in the vicinity of the stream channels and at a distance of three or four miles from the nearest Protoceras channel they are only occasionally seen. These nodules represent the recurrence of a period of greater aridity (but not desert conditions) when the lime was deposited by evaporation of ground water drawn to the surface by capillarity. Their greater abundance in the immediate proximity of stream channels suggests that the ground was there more completely saturated with water than elsewhere. The waters of the streams draining from the Black Hills should have a fairly high calcareous content, for they cross the outcrops of the thick Carboniferous limestone, which averages nearly 500 feet in the southern Black Hills. The thickness of this middle division of the Leptauchenia beds is 65 feet in the Cedar Butte section. On the edge of Cooney Table where the section was measured the upper limit of these nodular ash beds was obscured by a Protoceras channel.

The Protoceras channels are commonly developed through the Lower and Middle divisions of the Leptauchenia beds, and as stated above, at one point, cut down into the upper reddish clays of the Oreodon beds. They are principally developed in the valleys of Corral and Cottonwood Creeks in the Big Badlands, and constitute a pronounced topographic feature at the head of the central and western branches of Corral Draw, about 2½ to 3 miles southwest of Cottonwood Pass. Here the channels cap the divide between White and Cheyenne River drainage for about half a mile, and by reason of their massive character remain supported on vertical pillars of clay, sometimes 200 feet or more above the adjacent draws. These channels are distributed vertically through about 130 feet of beds and the

FIG. 1. Several levels of Protoceras channels, overlain by the nodule-bearing Leptauchenia ash beds, along the Corral Draw-Cottonwood Creek divide.

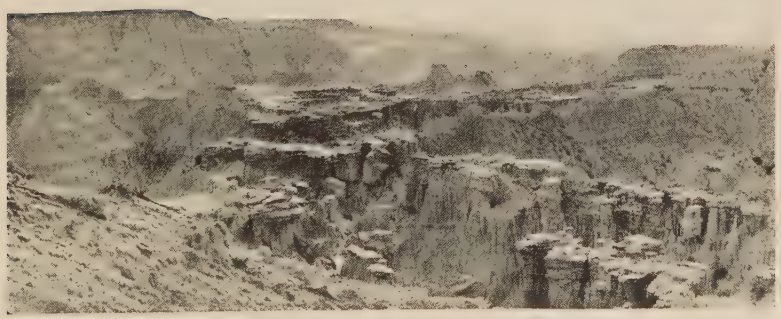


FIG. 2. Looking west along the Corral Draw-Cottonwood Creek divide, showing a probable meander in the course of a Protoceras channel.

FIG. 1. White Ash layer with underlying Leptauchenia beds of Division (3) on the top of the Cedar Butte, 12 miles south of Sheep Mountain.

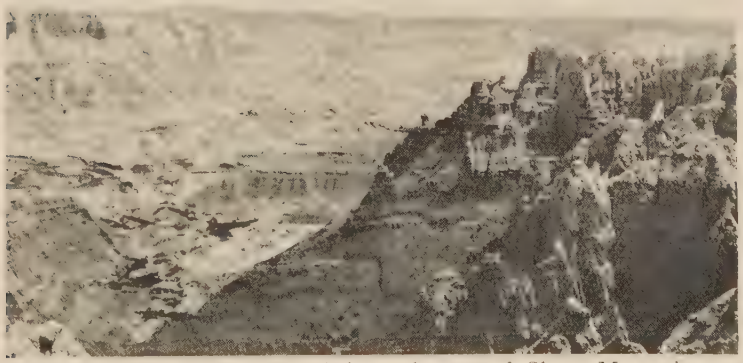


FIG. 2. Looking southeastward from the top of Sheep Mountain toward Arnold's ranch, showing, in the foreground, Division (3) of the Leptauchenia beds.

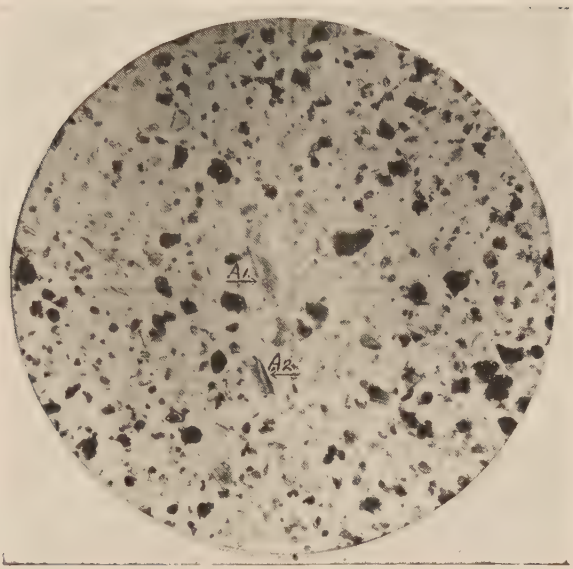



FIG. 1. Microphotograph of volcanic ash from the White Ash layer, Cedar Pass section, Interior, S. D., showing two large pumice grains (A1 and A2) with capillary tubes. Most of the smaller grains are angular fragments of volcanic glass.

FIG. 2. Two vertical pipe-like concretions from the White Ash layer, Sheep Mountain. A. Large concretion about 2 inches in diameter and 6 to 8 inches in length, filled with darker-colored material than that on the margin of the concretion, where there is a lighter border. B. A smaller concretion with a hollow central tube which is lined with minute crystals of zeolites.

stratigraphic positions of several of the more pronounced massive lenses of sandstones is given in Columnar section *A*1, Fig. 5. The highest channel (No. 1) is situated on the edge of Cooney Table at the Quinn-Corral Draw divide. Plate VI., Fig. 1, is a photograph of a heavy channel sandstone 25 feet in thickness, which for a distance of nearly a quarter of a mile caps the Corral Draw-Cottonwood Creek divide. Several levels of caliche nodules of the middle division of the Leptauchenia beds are visible above the channels. On the map, Fig. 7, the distribution of Protoceras channel sandstone outcrops in Corral Draw and Cottonwood Creek is shown. The general direction of the Protoceras channels from the Corral-Cottonwood divide for three or four miles into Cottonwood Creek is about S. 60° E., which is also the direction of maximum initial dip in the sediments, and hence probably the direction of the original graded slope of White River time. Protoceras channels have also been observed at Interior and are described and figured by Ward.[53]

One Protoceras channel sandstone from Cottonwood Creek, analyzed mechanically, contained 17.5 per cent. of heavy minerals (gravity greater than 2.95), of which over 90 per cent. were garnets. Pebbles of mica schist and quartz schist, tourmaline and staurolite, also occur in this sample, and its grains are of various sizes, showing poor sorting. Frequently large fragments derived from the Leptauchenia ash beds are found in the channel sandstones and they may constitute a high percentage of the material locally. At one point in Cottonwood Creek a layer of brownish pebbles, which, upon analysis, were found to be caliche nodules from the middle division of the Leptauchenia beds, was found in the middle of a section of about 10 feet of fine-grained greenish micaceous sands. This shows that the caliche nodules had been formed and were subject to erosion at the time that this sandstone was deposited. The abundant deposition of this material derived from the adjacent flood plain was probably due to local cloudbursts of unusual severity.

An interesting parallel to the White River sandstones is offered by those of the Siwaliks, of late Tertiary age, which were deposited by sediment-laden streams from the Himalayas when they spread out

[53] Op. cit., p. 30 (Bed F), and Plate XV.

on the Indo-Gangetic plain. McMahon [54] notes that the "Siwalik sandstones contain largely quartz, muscovite, garnet, schorl tourmaline, and some weathered feldspar . . . and some limestone pebbles." He believes that most of the material is derived from the Dalhousie granite of early Tertiary age. The mineral aggregate described here is almost the same as that found in the sandstones of the White River, but volcanic glass does not seem to have been a factor in the Siwalik deposits.

*Division* (*3*).—The upper division of the Leptauchenia beds is a massive, more thoroughly cemented sequence, which weathers with an irregular surface due to the presence of a succession of harder and softer beds. The stratification is much more apparent than in the clays below, with cross-bedding sometimes developed. No Protoceras channels have been observed cutting these beds. The cause of the marked stratification of this series is not apparent to the writer unless it represents rapid oscillations of climate. Exposures occur only on the edges of Sheep Mountain (Plate VII., Fig. 2) and in the Cedar Butte section (Plate VII., Fig. 1), where there is a thickness of 72 feet. In Corral Draw it has been cut out by the alluvium on top of Cooney Table. It gives rise to the pronounced organ-pipe type of weathering which is so splendidly exhibited on Sheep Mountain, and is also exposed along the south side of White River below the White Ash layer (defined below), but this section has not been visited by the recent Princeton expeditions. Volcanic glass and pumice are very abundant in this division, probably averaging more than 50 per cent. of its clastic material.

In comparing the sections in the Big Badlands with that at Interior, Jackson County, about 60 miles to the northeast, it will be at once noticed that the whole thickness of the Leptauchenia beds has been greatly reduced. The total thickness of the Leptauchenia beds at Interior is 72 feet, where it is bounded at the base by the Upper Oreodon reddish clays, from which it is separated by a light-weathering band like that exposed in the Big Badlands at the contact, and, at the top, by the White Ash layer. The Interior section, as previously published, included in the Upper Oreodon beds all of the

[54] Records of Geol. Survey of India, Vol. XVI., Pt. 4, 1893.

upper clays to the base of the White Ash layer. The presence of *Leptauchenia* 50 feet below the White Ash layer had not been observed at that time, nor had the persistence of the latter and its value for correlation been determined. The revised Cedar Pass section is shown in Fig. 6, *E*.

It is remarkable that while the upper member of the Oreodon clays persists with practically no thinning from the Big Badlands to the Interior section, the Leptauchenia beds thin from about 170 feet at the Cedar Butte to 72 feet at Interior, the thickness of the upper member alone in the Big Badlands. It is interesting to note that Ward [55] divides the series from the top of the Oreodon beds to the White Ash layer into three divisions which he describes successively as (*a*) "a gray massive sandy shale with scattered poorly defined sandstone nodules, (*b*) a light gray, fine-textured sandstone noticeable for its pronounced bedding, and (*c*) a massive fine sandy shale resembling (*a*)." In view of the rapid thinning of the Leptauchenia beds away from their source of material it would be interesting to know whether all of its members persisted or whether one or more of them were missing. The lower member in the Big Badlands seems to resemble (*a*) of the Interior section and the upper member of the Big Badlands seems more like (*b*) of the Interior section, as a pronounced stratification is a characteristic of both. Ward does not mention the presence of *Leptauchenia* at Interior, but they were found quite abundantly on either side of the road running through Cedar Pass about 200 yards north of the top of the pass on each of our three visits to this section. They seem to be most abundant in his division (*b*). *Miohippus* and *Eporeodon major,* both typical fossils of Leptauchenia age, were also found here.

At one or two localities in Cottonwood Creek irregular thin beds of almost pure white ash were observed in the Leptauchenia clays. The thickness of these beds was not greater than one or two inches. These are probably remnants of light ash falls preserved locally under favorable conditions.

*The White Ash Layer.*—The White Ash layer is one of the most persistent and interesting elements in the White River area. It rests

[55] Op. cit., pp. 29–30.

upon the upper division of the Leptauchenia beds and is clearly recognizable at all points through the region where the higher beds are exposed, the best sections being on top of Sheep Mountain, the Cedar Butte near the mouth of Cottonwood Creek, the Cedar Pass section at Interior, and the western part of the Wall of the Badlands five miles northeast of Imlay. It has in all sections a thickness of from 15 to 25 feet. Its base is clearly defined, but its upper margin is so nearly like the overlying grayish ash beds that it is hard to determine its upper limit close at hand. From a distance of a mile or so its lightness of color and greater resistance to weathering than the beds above and below cause it to stand out prominently as a distinct unit. It is exposed on the south side of White River for several miles east of the mouth of Porcupine Creek along the badland edge of the high plain south of the river. In nearly all the sections described by Darton in the western part of Nebraska [56] and in the Goshen Hole area of eastern Wyoming [57] there are either one or two ash beds in the upper part of the Brulé clays. These are spaced from 50 to 200 feet below what he terms the top of the Brulé clays. Matthew [58] writes: "A bed of volcanic ash lies near the top of the formation" (Rosebud) in the section of Porcupine Creek. It is possible that one of the two ash beds of western Nebraska corresponds to the latter and the other to the White Ash layer of the Big Badlands sections. The thicknesses of the ash layers mentioned by Darton vary from six to twelve feet.

Matthew suggested the White Ash layer south of White River as the base of the Rosebud formation in his type section on Porcupine Creek. He places the Rosebud formation in the Lower Miocene, because [59] "*Parahippus* which shows a decided advance over *Miohippus* in feet, though near it in teeth, and evidently an invading type appears in the Rosebud." This correlation is only tentative and may be changed by further field work.

The following section and description [60] of the occurrence of Ter-

[56] U. S. G. S., Prof. Paper No. 17, pp. 37–40; also plates and figures.

[57] U. S. G. S., Geol. Atlas of the U. S., Hartville Folio (No. 91), Columnar Section Sheet, Sections 2 and 4.

[58] *Bull. Am. Mus. Nat. Hist.*, Vol. 23, p. 173.

[59] Personal communication.

[60] Darton. U. S. G. S., Prof. Paper No. 51, pp. 67–70.

tiary ash in the Big Horn Mountains east of Canyon Creek is valuable, as it supports the theory that the White River ash was derived from regions to the west of the Black Hills:

"Sandy clay soil..... 6 feet
Gravel of crystalline rock with lenses of volcanic ash near the base, and with occasional boulders up to two feet in diameter..... 60 feet
Volcanic ash, arkose, fragments of igneous rock, etc., indistinctly stratified ..... 73 feet
Conglomerate cemented by lime carbonate, boulders up to 4 ft. in diameter and generally well rounded..... 22 feet

The amount of volcanic ash in this section is large, and it appears to have been laid down by water, although some of the finer portions may be wind blown. The nearest eruptions from which it could have been derived, so far as known, are in the great volcanic area west of the Bighorn Basin. As most of these eruptions occurred in Tertiary times and as volcanic ash is generally characteristic of the Tertiary beds in the Black Hills and farther east, the Bighorn deposits are provisionally referred to this age. . . . The conglomerate with lime matrix and volcanic ash appear at other outlying localities. . . . Evidently the deposits originally extended over a broad area east of the mountains as shown by the widely scattered remnants . . . and since their deposition there has been extensive erosion to the present low level of the plains."

The very wide distribution of volcanic ash of Upper Oligocene and Lower Miocene age is apparent from the above data. The Bighorn section is not dated, but it may well be of White River age, as outliers of the White River are found in pockets in the pre-Cambrian rocks of the Black Hills and capping high divides on their flanks. The significance of this evidence as to the source of the volcanic material and the extent of eruptive vulcanism will be discussed in a later chapter.

The presence in the White Ash layer of abundant vertical pipe-like concretions with tapering terminations, and small central hollow tubes averaging from $\frac{1}{16}$ to $\frac{1}{8}$ inch in diameter, offers an interesting problem. The central tubes are lined with minute crystals of zeolites often of radiate structure. The varieties of zeolites have not been determined, but mordenite (index of refraction 1.465) seems to be one of them. The latter also occurs in needle-like crystalline development lining small cavities in the body of the ash. These concretions and zeolite-filled cavities are found only in the ash, most markedly in the White Ash layer at the base of the Rosebud, and also in

the ash beds immediately above and below. The average length of these concretions is from four to six inches. The average diameter is one to two inches. Their shape resembles that of a coprolite (Pl. 8, Fig. 2). These concretions can be well observed in the Stony Pass section of Sheep Mountain.

Walker [61] has described a structure in the Basalt flows of Nova Scotia which seems to present a fairly close parallel to these concretions. He states: "In certain parts of this section (south side of the Bay of Fundy) the writers observed a peculiar structure in the basalt which consists of a development of vertical pipes or cores. These are sometimes coarsely amygdaloidal. At other times, where the basalt is fairly dense, cylindrical cores are developed which appear to be of the same rock type as the general mass in which they occur. At one locality (1½ miles east of Morden) the reddish amygdaloid in the low cliffs along the shore is penetrated by vertical cylindrical structures from one to four and a half inches in diameter and at times two yards in length. The material of these cylinders is characterized by the presence of white amygdules of zeolites from ⅛ to ½ inch in diameter which are more abundant near the margin of the cylinders than at the centre, while the main mass of the basalt is not marked by any prominent amygdaloidal structure. On a flat surface of basalt below high tide . . . the writers observed within a radius of four feet 25 tubes, 18 of them from 1¼ to 1¾ inches in diameter." He states that the mineral mordenite first discovered at Morden, N. S., occurred in the cylindrical concretions along with the other zeolites.

The explanation which he believes most suitable is as follows: "It is simpler to regard the tubes as caused by ascending currents of gases, probably water vapor rising from the wet floor beneath the igneous mass. This gas would make its way into the magma through cracks in the chilled floor of basalt and operate under considerable pressure in a continuous stream during the period of consolidation. The ascending gases, owing to the lessened pressure and consequent expansion, should have a cooling effect on the walls of the tube, and so cause this part of the mass to consolidate first and be finer in grain. . . . In some cross-sections . . . there is a well-marked concentric

[61] "Contribs. to Canadian Mineralogy," 1922, Univ. of Toronto Studies, Geol. Series, No. 14, pp. 5–12.

arrangement surrounding the pipes, that nearest the pipes being finer in grain and less amydaloidal than elsewhere. The open tubes like those found at Ste. Croix cove might be due to gas pressure at the end driving out the last available magma and leaving openings for the deposition of quartz and zeolites." [61a]

The conditions of formation of the concretions in the White River formation in the Big Badlands must differ notably from those described above, as the volcanic material was there both solid and cool at the time of its deposition. The concretions in the White Ash layer do not resemble those from the basalt in appearance, but the similarity in the shape and size of the tubes and their spacing and the presence of zeolites, notably mordenite, in both indicates that their mode of formation may have been at least similar. Griggs [62] has shown that solutions derived from volcanic ash may be strongly impregnated with acids even after the ash has been carried over a thousand miles in the air, so that brass fittings on automobiles in the Puget Sound region were tarnished by acid from the ash of the Katmai eruption. Therefore the cylindrical pipes filled with these tubular concretions may have been formed by gas explosions or the upward escape of imprisoned water, $CO_2$, or even air, and the zeolites produced by crystallization of material derived from the ash. In one or two cases one concretion was observed to have slipped over another, with the production of a slicken-sided surface, which Lawler [63] attributes to vertical stress.

*The Rosebud Beds Above the White Ash Layer.*—In the sections at Sheep Mountain and Cedar Pass, Interior, the beds above the White Ash layer closely resemble those immediately below it. They are gray or pinkish in color and consist largely of volcanic glass and pumice. The exposures of the Rosebud are in steeper slopes than those of the White Ash layer, as they are not so thoroughly consolidated into rock. At the top of the section at Sheep Mountain, the Rosebud beds are a little more sandy in character than immediately above the White Ash layer, and the same is noticeable at Interior. In the section northeast of Imlay, on the divide between Sage Creek and

[61a] Ibid.

[62] "The Valley of Ten Thousand Smokes," Nat. Geog. Soc., 1922, pp 25–29.

[63] *Am. Jour. Sci.*, Vol. V., Feb., 1923, p. 172.

White River drainage (Fig. 6, *D*), a coarse stream channel sandstone with numerous large rounded pebbles of ash, evidently derived by the stream from the erosion of its banks, occurs about ten feet above the White Ash layer, capping the section. At Interior, east of Cedar Pass, a heavy sandstone 140 feet above the White Ash layer caps the section. This is bed *F* of Ward's section of the Protoceras beds.[64] The similarity of these Rosebud ash beds to those of Leptauchenia age and the presence of channels in them resembling the Protoceras channels indicates that, though these beds may be classed as Miocene on faunal grounds, the depositional conditions were not greatly changed. Matthew[65] gives a thickness for the Rosebud on Porcupine Creek of 500 feet and states that, although "the beds at the bottom approximate the rather hard clays of the Upper Leptauchenia beds, they become progressively softer and sandier toward the top and are capped at Porcupine Butte by a layer of hard quartzitic sandstone." The Lower Rosebud beds are the highest Tertiary formations exposed in the area of the Big Badlands. The evidence on the post-Miocene history of the area is treated in a later chapter.

### III. Physiography and Climate of White River Time.

The climate existing in the Great Plains region in Oligocene time is one of the most important of the environmental factors conditioning the life of the time. The best absolute measures of climate are supplied by fossil plants, as these, according to Knowlton, are the most sensitive indicators of changes of temperature or moisture. Unfortunately there is very little floral evidence to be derived from the White River beds (at least in their South Dakota exposure), but what little is to be found may be very instructive. In three seasons in the field only one petrified tree trunk (*Celtis*) has been found, in the basal Titanotherium beds in the west branch of Corral Draw, above referred to. However, through the clays of the Oreodon beds, wherever a careful search is made, a fair collection of fossilized seeds of *Celtis* (hackberry) may be found. They must occur through the clays in millions and Dr. Chaney[66] believes that their abundance may

[64] Op. cit., p. 30.

[65] *Bull. Am. Mus. Nat. Hist.*, Vol. 32, p. 169.

[66] Personal communication.

"have an important bearing on the physical conditions under which the sediments were laid down. A living member of the genus, *Celtis reticulata,* which grows in the southwest, is common along dry or intermittent water courses in the Colorado desert. In one of my Great Basin floras, probably of Oligocene age, I am finding leaves of *Celtis* rather abundant. These are more closely related to *Celtis reticulata* than to any other living form. There seems to be little doubt as to the habitat significance of certain members of this genus." An examination of the data on plant associations in Harshberger's "Phytogeographic Survey of North America"[67] shows that, although *Celtis* has a very wide range among deciduous forest associations, it is capable of persisting under conditions of poor sandy or gravel soil, or climatic extremes where many of its associates in the deciduous forest can not hold their own. Thus it is among the forests being destroyed by advancing sand dunes on the New Jersey coast; it grows on the sand dunes on the Barrier Islands of the Gulf Coast of Texas; in the sandhill country of western Nebraska it is common in narrow belts bordering the stream courses; it is characteristic of the foothill belt of the eastern Rocky Mountains; it is one of the trees derived from the east, extending farthest west into the Great Plains of the northern states, and is one of three eastern trees extending farthest into the Texas Plateau country. It grows along streams and flood plains in the Rio Grande and Chihuahua desert country, and in valleys along the eastern flank of the Sierra Madre. From the persistence of *Celtis* in the warm desert regions of Chihuahua and its endurance of the cold winters of the northern great plains it is evident that it offers no key to the temperature conditions of White River time. The fact that *Celtis* grows at present in many regions of slight rainfall shows that conditions of semi-aridity may have existed in White River time in the Great Plains region, where *Celtis* seems to have been one of the most important elements of the flora. *Celtis* probably grew along the courses of the streams of the Great Plains in Oligocene time, much as cottonwoods follow the modern badland draws.

The evidences of climatic conditions from the sediment itself may now be considered. While the suggestion of a semi-arid climate has

[67] J. W. Harshberger, "Phytogeographic Survey of North America," N. Y., G. E. Stechert & Co., 1911.

been brought forward, it is not to be thought that the climate was uniform throughout the duration of White River time. There were times when extensive shallow lakes characterized the surface of the plain, supporting a rich invertebrate fauna. There were times of greater aridity when ground water was drawn to the surface and deposited its dissolved calcareous material there as a cement for the silts of the surface, and there were evidently times of still greater aridity when gypsum was deposited, as described by Ward [68] and Fraas.[69] Furthermore, in the beautifully exhibited color banding of the White River clays and silts there are evidences of minor rhythmical fluctuations in climate.

As the question of the part played by climate and climatic changes in the deposition of the White River sediments is intimately tied up with the physiographic conditions of the region at the time of deposition, it will be well to review here the views on the physiographic conditions during White River time expressed by several geologists who have studied the area. The following discussion shows the gradual change of geological opinion as to the origin of the Tertiaries of the Great Plains from the volcanoes and convulsions of Culbertson and the lakes of Dutton and Hayden to the prairie loess of Matthew, the subaërial delta of Johnson, the lakes and flood plains of Fraas, the rivers and flood plains of Hatcher, and the rivers and shallow ephemeral lakes of Ward.

Thaddeus Culbertson in 1850 visited the White River Badlands and made a small collection of fossils for the Smithsonian Institution in the valley of Bear Creek, about three miles northeast of the present town of Scenic. He was the first to describe these badlands, and though not a geologist, was greatly interested in the problem of how they were formed. In his diary [70] he writes: "In thinking of how these lands were formed, it occurred to me very forcibly that it was by some convulsion of nature by which the ground sunk—the hills were not elevated, but were left so by depression of the surrounding land. . . . A few miles from the creek we passed over some hills that

[68] Op. cit., p. 22.

[69] *Science*, N. S., Vol. XIV., No. 345, Aug. 9, 1901, pp. 210–212.

[70] 5th Ann. Rept. of Board of Regents of Smithsonian Institution, 1851, pp. 92–93.

gave evidence of having experienced the most violent convulsions; these appeared to have been upheaved and to have experienced the action of fire; one place suggested the idea of a volcanic crater; it was a slight hollow and contained a number of small rocks different from any around it."

Dutton[71] wrote: "I know of no more impressive and surprising fact in western geology than the well-attested observation that most of the High Plateau area has been covered by fresh-water lakes. . . . The marvel is not in the fact that here and there we find the vestiges of a great lake, but that we find these vestiges everywhere. The whole region, with the exception of the mountain platforms and pre-existing mainlands, has passed through this lacustrine stage. . . . We know that the Miocene climate of the west was moist and subtropical. This is indicated by the great extent of fresh-water lakes in some portions of the west, their abundant vegetable remains, and the exuberance of land life."

Hayden (1867)[72] wrote: "I would infer that this great fresh-water lake (White River) must have spread over 150,000 sq. miles. . . . With the commencement of the Tertiary was ushered in the dawn of the great lake period of the west. The evidence seems to point to the conclusion that from the dawn of the Tertiary period, even up to the commencement of the present, there was a continuous series of fresh-water lakes all over the continent west of the Mississippi River. . . . Every year, as the limits of my explorations are extended in any direction, I find evidences of what appear to be separate lake basins, covering greater or less areas."

Matthew[73] was one of the first to abandon the lacustrine theory for the origin of the White River sediments. He believes that the larger part of the finer clays of the White River of Colorado are "chiefly eolian deposits, similar in origin to the prairie loess . . . picked by the wind from exposed surfaces and deposited on the sodded, or partially sodded, prairie surface." He believes that most of the sandstones, especially those of lenticular character, represent river deposits. He also expresses the opinion that the fauna lived in

[71] U. S. G. S., Monograph II., p. 216.

[72] Geol. Surv. Terr., 1st Ann. Rept., p. 58; and 2d Ann. Rept. pp. 114–115.

[73] *Am. Naturalist*, Vol. 33, pp. 403–408, May, 1899.

an open grassy region, and is paralleled by the fauna of the dry high plateaus of Africa of today.

Johnson[74] (1900) rejects the lacustrine theory and describes the Tertiary of the Great Plains as a debris apron or subaërial delta deposit made by distributary streams after emerging from the front of the Rocky Mountains in narrow canyons overloaded with sediment, on a gently inclined plane away from the mountains. This debris apron accumulated on a graded slope or gradation plane which had been eroded on the surface of the older Cretaceous deposits. He states (p. 622): "A series of streams from a mountain range, which in humid lands would persist upon independent courses and excavate valleys, may in arid lands unite by broad branching and interlacing flow and build up the original surface to a smooth and far extended apron of debris. This debris apron, having the profile of a graded stream bed along all lines in the direction of its slope, will be a gradation plane, sensitive as a whole to any disturbance by outside influences, of the equilibrium between its opposite grading forces, just as the single profile is sensitive."

Professor Fraas,[75] of Stuttgart, after visiting the White River Badlands in 1900, expressed the following opinion of the physiographic conditions of White River time: "At the beginning of the Oligocene a broad, slowly moving stream spread out toward the east and formed a broad, widespread and uniform delta landscape (Titanotherium beds). This even, swampy land was dry during the dry seasons, but was flooded in every high-water period; besides the water the wind frequently took part in the transport of dust and materials. The concretions are structures of the percolating waters (Lower Oreodon beds, numerous land mammals). Now followed a long period in which this region was flooded by a shallow rather than deep lake. The inflow of water did not exceed the evaporation and so through the varying concentration there was a precipitation of the dissolved materials which gave rise to the banded layers. In the same manner the gypsum and barite in these layers is explained. Stronger currents poured in sand, which accumulated in low elevations (Middle Oreodon beds). At last there came a widespread eolian condition in the

[74] U. S. G. S., 21st Ann. Rept., Vol. 4, 1900, pp. 612–656.

[75] Op. cit.

form of loess, which spread out upon the gradually retreating or evaporated levels of the Lake (Leptauchenia beds)."

Hatcher,[76] who probably had a better acquaintance with the White River formations than any other geologist, through his many seasons of collecting in them, rejected the lacustrine theory and believed that "the sandstones, conglomerates, and a portion of the clays were deposited in river channels, while the limestone lenses, so rich in the remains of aquatic plants and mollusks, originated in shallow ponds and lakes scattered over the higher table-lands and the broad flood plains of the rivers, where for the most part the finer clays were deposited by occasional inundations and through the agency of winds." He compares this with the confluent flood plains of the Upper Paraguay, Amazon, and Orinoco rivers, an area "equal to or greater than that occupied by the Oligocene and Miocene deposits of our western plains, with all the physical conditions necessary for the deposition and present distribution of the sandstones, clays and conglomerates, together with the preservation of remains of the faunas characteristic of each."

Recently Ward[77] has revived the lacustrine theory in a modified form. He accepts the fluviatile origin of the stream channels, but says: "The fact that the bulk of the Badland sediments are fine textured and that there is no apparent coarsening of the texture except quite near the Black Hills indicates that weathering at the source must have been extensive and deep. At the same time the soils developed by weathering were not thoroughly leached nor completely oxidized." To explain the alternations of shales and sandstones (other than channels), he believes that "intermittent and recurrent uplift" is a more satisfactory explanation than climatic changes. In regard to flood-plain deposit he says: "The clays, of course, required water for their deposition. While some of the smaller thin beds may have been deposited as flood deposits on a flood plain, most of them must have been laid down in lake waters. The chief reason for thinking so is the marked continuity of the beds, their uniform character, and considerable thickness. . . . Clay deposits on present-day flood plains, such as the broad Missouri . . . are commonly thin and do not

[76] Proc. Amer. Phil. Soc., Vol. XLI., April, 1902, pp. 113–131.

[77] Op. cit., pp. 36–40.

keep their continuity for more than a few hundred feet, and very rarely can a bed be traced a quarter of a mile. The shale beds of the Tertiary are continuous commonly for a quarter to three quarters of a mile and a few are a mile or more in extent, while all of the Titanotherium and at least one shale bed of the Oreodon are continuous over the whole area." He believes that the climate "must have been humid and temperate or cool and the relief moderate."

From the above quotations it will be clear that the interpretation of the climate and the climatic changes of White River time depends fundamentally on which of the many diverse views regarding the conditions of sedimentation is adopted. Also the climatic significance of alternate bands of greenish and pink or red silts and clays should be understood, and here again there is a diversity of opinion. Tomlinson [78] believes that the ferruginous material of red beds was transported and deposited almost, if not quite, wholly as a mechanical sediment, both independently and as a coating upon grains of other materials, and that in many cases the green shales or sandstones alternating with the red are caused by the reduction of the ferric iron by organic material in the original sediment. Barrell has suggested that the green or gray strata in red beds are coarser than the red and their deoxidation may be due to the fact that [79] "more abundant ground waters in the sands may have kept out the air and permitted the organic matter to accomplish its effects." In another place [80] he states that "where lightness in color is due to chemical causes it is to be noted that the first result of the action of fermenting organic matter upon ferruginous clays is a change of color from rusty to bluish or greenish by the reduction of ferric to ferroso-ferric hydrate. Afterward, if the action be continued, the solution of ferrous carbonate may be formed, and the greenish or bluish color may disappear. The importance of this reaction lies in the fact that the blue or green, wherever it occurs, indicates a lack of aëration usually by the stagnation of water in consequence of imperfect drainage. . . . Where such colors are rather abundant, however, over broad areas of non-marine formations, a mean rather than an extreme climate is indicated."

[78] *Jour. of Geol.*, Vol. 24, 1916, pp. 153–179, 238–253.
[79] *Amer. Jour. Sci.*, 4th Ser., XXXVI. (1913), p. 469.
[80] *Jour. of Geol.*, Vol. 16, 1908, pp. 293–4.

In the White River formation the green silts and sands generally occur in lens-shaped bodies. The stream channels are generally greenish colored, and there are finer-grained outliers of the channels frequently showing abundant flakes of muscovite mica. Farther away from the channels are beds of fine green silt hardly distinguishable from the reddish clay in composition or texture. The green beds are rare away from channels through most of the series, but in the Middle Oreodon beds there is a very widespread development of greenish sands and silts (Division 4). Plate I., Fig. 1, shows this zone clearly as developed in Battle Creek Draw. This widespread green zone may represent a period of greater rainfall when a broad river flowed over the area where the heavier sandstones were developed and frequently flooded the plain away from its valley, perhaps leaving stagnant pools here and there on the surface of the plain between times of flooding. This would seem to be the condition most likely to prevent the iron in the clays and sands from being oxidized to a ferric condition. The green bands may be considered then to represent deposits made under a cover of water, as stream channels, or on a soil surface saturated with water, such as might occur immediately adjacent to stream channels. It may be noted here that the Titanotherium clays, though gray and spongy on the surface, are moist a foot or so below the surface and are uniformly colored pale green.

In Ward's recent paper, above cited, the opinion is expressed that flood-plain deposits would not be as extensive and uniform as those found in the White River. The uniformity and extent of deposition of certain layers is surprising, but the lithology, fossil content, and structures of the deposits seem to demand deposition on a surface generally exposed to the air and only occasionally flooded. Davis [81] describes a flood plain in Central Turkestan that is so similar in character to that postulated for the White River area that a little of his description may be profitably quoted. "The surface was absolutely plain to the eye except for the dunes and the dunes departed from the plain only as wind waves at sea depart from a calm surface. Although apparently level, the plain has slope enough to give the Tejen, the Murg-ab and the Amu rapid currents, in which these rivers carry forward a great amount of mountain waste. . . . The rivers have

[81] "Explorations in Turkestan," Carnegie Inst. Pub. 26, 1905, p. 54.

great variations in volume. . . . We were fortunate enough to see the Tejen and Murg-ab in flood. The former overflowed its channel and spread in a thin sheet for miles over the plain. The latter would have spread but for the restraint of dikes at Merv. Some of its waters had escaped farther upstream, and came to the railroad, wandering across the plain among the dunes, a curious combination of too much and too little water supply. The most notable feature of the region was the absence of valleys. The rivers had channels in which their waters are usually restrained, but there were no valleys in which the river floods were limited. The plains were open to overflow as far as flood supply held out." The difference between the flood plains of the western region of today such as those of the Missouri River, cited by Ward, and those which must have been the seat of deposition of the White River beds is that these modern rivers are entrenched below the level of the high plains, and it is therefore impossible for their flood waters to extend farther from the stream than the sides of the valleys. The present cycle in the plains region is primarily one of degradation and is characterized by local and temporary flood plains in contrast to the broad uniform plains of aggradation of middle Tertiary time.

As the writer's interpretation of the significance of red and green colors in the sediments and of the physiographic conditions of the area during deposition have been outlined, a brief sketch of the climatic and physiographic history of White River time may now be presented.

After the Cretaceous period a long time of erosion with peneplanation ensued under mild or humid conditions, during which a residual soil mantle rich in ferric oxide was accumulated. This soil mantle reached a depth of 30 or 40 feet, the thickness of the "Interior" formation. This is the initial graded slope of erosion upon which the plain of aggradation formed by the mantle of Oligocene and Miocene sediments is based.

At the beginning of White River time greater aridity removing the vegetation or, more likely, primary movement of uplift in the Black Hills to the west, caused the entrenchment of streams in this old soil surface, with the result that, in places, the whole of the

residual soil was removed and dissection continued for a short distance into the Pierre shale. The rejuvenated streams engaged in this dissection carried with them pebbles from the Black Hills which from their freshness indicate quite rapid transportation. Gradually the valleys were widened and soon a more gentle relief caused the streams to wander somewhat upon the surface of the valley floor depositing sands in their channels and steeply cross-bedded silts as lateral delta terraces on the sides of the valleys. Thus, with perhaps a slightly more arid climate the streams gradually aggraded the valleys which they had cut in the old residual soil surface until once again a plain existed. The iron from the old soil was contributed sufficiently to the silts of the valley to color these beds strongly, as mentioned above. When the streams of Titanotherium age had aggraded to the level of the old plain they were no longer bound in by valley walls and were free to wander at will across the plain. Thus when torrential downpours in the Black Hills brought down sheets of water they were not limited by the sides of the valleys, but spread far and wide over the plain, each flood leaving an additional thin sheet of silt. A mild climate with sufficient rainfall existed and animal and plant life was probably abundant. Local lakes existed over the plain where slight depressions ponded the waters from the floods and held the local rainfall and in them flourished a rich algal growth with associated fresh-water invertebrates which formed the many local lenses of limestone now found through the Titanotherium beds.

After a long period of time erosion again predominated over sedimentation, with conditions favorable for carrying the silts from the hills to a greater distance before their deposition. Also with a more humid climate the Black Hills would be more completely covered with vegetation and streams emerging from them would not be so overcharged with sediment as under the previous more arid conditions. We do not know the length of time represented by this erosion interval, but it was probably shorter than that represented by the deposition of the Titanotherium beds. At the close of this period of erosion all the depressions on the surface seem to have been the sites of local ponds in which fish, cyprids, fresh-water gastropods, and algæ flourished. Some of these may not have been actual ponds, but rather damp marshy meadows.

With the close of this algal pond stage climatic conditions swept to an arid extreme which may have caused the disappearance of a large part of the cover of vegetation. In the opinion of the writer this climatic change may also have been responsible for the sudden disappearance of *Titanotherium*. In the sediments it is represented by the marked increase in the amount of calcareous cement. Again shallow streams meandered across the plain and spread broad sheets of silt many miles away from their channels. A large and varied fauna roamed over the grassy plains, and an aquatic fauna typified by the massive rhinoceros *Metamynodon* frequented the river channels. Several times after a period of flood the surface of the plain remained dry, perhaps for many years, and the surface silts were cemented to a hard caliche or nodular level by the deposition of the soluble content of the ground water when it was evaporated. As the ground water was drawn to the surface by capillarity a small film of water would remain around each fragment of sand or silt, and when this film was evaporated a thin coat of cement would be deposited on the surface of the grain. Gradually these films grew in thickness until they joined adjacent grains and eventually formed the whole into a solid mass. This condition was repeated several times during the deposition of the Red Layer. The fact that the caliche nodules are most strongly developed in the vicinity of stream channels, as mentioned above in connection with the Lower Red layer (Division 1 of the Oreodon beds), is probably due to the fact that the soil was more nearly or more frequently saturated with water here and consequently contained a larger amount of carbonates in solution than did the clays away from the stream channels.

After a long period of caliche development, there was a change to a somewhat more humid climate and stream channels became more numerous, and again local ponds with fresh-water faunas were developed over the surface of the plain. This zone is characterized by more frequent alternations of pink and green sediments. It was still, however, apparently more arid than Titanotherium time, as the sediments contain a larger amount of calcareous cement than did those of the latter. This period was closed by a short recurrence of caliche-forming conditions representing only one period of semi-aridity, as

there is only a single level of nodules (the Upper Nodular layer). The Upper Nodular layer was followed by even more humid conditions than those preceding it, as the beds of division (4) are predominantly green and coarser in grain. As stated above, this green coloring probably represents widespread flood-plain conditions and probably a wider main channel than that of earlier White River time. The flood plain of the upper Mississippi near Lacrosse, Wis., with extensive bottomlands on either side of the river covered with water the greater part of the time is perhaps a similar case, except that the Mississippi is deeply entrenched below the level of the plain, while the Oreodon beds stream flowed in a shallow channel on the surface of the plain. This condition persisted for a period about equivalent to that between the lower and upper caliche levels and was followed by a recurrence of conditions of greater aridity, when red clays far predominate over green and channels are few and small. No caliche beds were observed here, partly because almost no channels are seen at this level.

Gradually another factor was impressing itself on these previous rhythms of climate and deposition, namely, increasing contributions of volcanic dust from outside the drainage areas of the White River streams in this district. As the wind-transported ash was probably distributed quite uniformly over the whole area, the Black Hills as well as the badlands, and as it would form a light unconsolidated deposit wherever it fell, the streams would naturally easily remove the ash from the surface, and from this time on it would be an important element in the stream-transported sediments as well. Furthermore, the erosion and transportation of the normal clastic sediment from the Black Hills might be to some extent reduced if the carrying capacity of the streams was filled by the easily eroded ash.

At the beginning of Leptauchenia-Protoceras time there seems to have been a slight return to more humid conditions, as stream channels became more abundant and extensive, but there soon ensued a period of caliche formation similar in character to that of the Lower Nodular layer and resulting, as did the latter, in a series of levels of nodules probably each representing old land surfaces. Also, as in the former case, the animals of the plain are abundantly preserved in

the caliche levels. The only difference between the Oreodon and Leptauchenia caliche nodules is that in the latter volcanic ash generally forms 50 per cent. or more of the clastic material of the sediments, and clay pellets are absent.

The massive distinctly laminated beds of the Upper Leptauchenia series directly below the White Ash layer rather resemble in their finer lamination the massive green sandstones of the Middle Oreodon beds, and it may be that they represent a recurrence of extensive flood-plain conditions with broad rivers. In these beds, as in the caliche layers underlying them, the primary character of the physiography and normal sedimentation is masked by the fact that from 50 to 75 per cent. of the clastic sediment is volcanic ash. The greater degree of cementation of these beds may be attributable with greater probability to solutions from the ash rather than to normal processes of evaporation, such as seem to control the cementation in the Titanotherium and Oreodon beds.

Following the massive laminated beds above referred to occurred the great showers of ash which completely dominated the sediments giving layers of pure ash over most of western South Dakota and Nebraska and eastern Wyoming. Here the ash completely dominates the sedimentary structure so that no suggestions as to the climate may be offered.

Continuing into the Rosebud there appears to be a recurrence of conditions similar to those before the deposition of the White Ash layer, and, according to Dr. Matthew, through the Rosebud there is a rather progressive change to more sandy sediments and an apparent increase in the importance of æolian action. The deposits of the Rosebud are too thin and too isolated in the Big Badlands north of White River to study the physiographic relations, but it can be stated that there still appear to have been river channels carrying coarse sediments from the Black Hills, and as far as can be seen in the Big Badlands area the lower part of the Rosebud sedimentation was as completely dominated by volcanic ash as was the sedimentation during Leptauchenia time.

The upper Miocene and Pliocene history of the region is a blank as far as deposition is concerned, for whatever sediment may have

been laid down during that time was later removed by erosion in the peneplanation of the surface, resulting in the formation of the high plain of which Hart Table, Sheep Mountain Table, and other high table lands in the district are remnants. The evidences of late Pliocene and Pleistocene physiographic and climatic history will be discussed in a later section.

Although the foregoing analysis of the climatic history is only tentative and may be changed materially by further investigation, it seems to show that there is, in the White River sedimentation, evidence of a very remarkable series of minor climatic cyclical or rhythmic changes, much like those which Huntington [82] has discovered in the Pleistocene history of the enclosed basins of Central Asia and in the climates of southern and western Europe of the past 2,000 years as narrated in classical and mediæval history. In the opinion of the writer, the fact that changes in character of the sediment such as caliche formation, alternations of green and pink silts, etc., are found to be uniform over such wide areas indicates, as Johnson [83] has suggested, that "this debris apron, having the profile of a graded stream bed along all lines in the direction of its slope . . . will be sensitive as a whole to any disturbance by outside influences." If this is the case, and if the climatic interpretation of continental sediments such as these can be standardized, the climatic history of the area may be deciphered with a preciseness heretofore unknown in the study of ancient climates.

*Evidences of Regional Uplift During White River Time.*—As the effect of strong uplift of the Black Hills might affect the sediments deposited on the plains to the east of the Hills in the same manner as would certain climatic changes, it is difficult to differentiate these two causes. If the Black Hills were suddenly raised much higher than they had been above the surrounding plains, the effect on the climate would be the production of greater rainfall in the Hills themselves, and of greater aridity on the plains to the east. In the opinion of the writer, marked uplift of the region of the Black Hills may have been

[82] "Explorations in Turkestan," Carnegie Inst. Pub. 26, 1905, pp. 182–216, 227–232, 253–275, 302–315. Also the "Pulse of Asia," "Palestine and its Transformation," and "World Power and Evolution."

[83] Op. cit., p. 622.

important in initiating the deposition of the sands and silts of Titanotherium age on the eroded peneplain of the Interior beds.

In the Oreodon and Leptauchenia beds certain subdivisions defined above have been recognized almost everywhere through the area of the Big Badlands. As complete sections from the base of the Oreodon beds to the top of the Leptauchenia beds are available both in the Big Badlands (Corral Draw district) and at Interior, about 50 miles to the east—*i.e.*, farther away from the Black Hills, the source of the clastic sediment of the White River—an interesting comparison may be made of changes in thickness observed in the subdivisions of the Oreodon and Leptauchenia beds. The accompanying diagram, Fig. 9, shows the generalized section of the Oreodon-Leptauchenia beds of the Big Badlands contrasted with that of the Cedar Pass section northeast of Interior. As the three subdivisions of the Leptauchenia beds recognized in the Big Badlands have not been distinguished at Interior, their respective changes in thickness can not be shown. It will be observed that the Lower Red layer (1), the color-banded silts and clays overlying this layer (2), and the upper reddish clays of the Oreodon beds remains remarkably constant, showing a variation of three feet or less in these sections separated by 50 miles. In contrast to these the Middle Oreodon sandstones or sandy silt beds (4) change from 50 feet in the Corral Draw sections to 24 feet in thickness, maintaining the same character at both places, and the Leptauchenia beds change from 192 feet to 72 feet in the same distance. The White Ash layer shows minor variations in thickness from point to point, but as it is not considered a stream-transported sediment, these would have nothing to do with uplift of the Black Hills or with climatic change. The rapid thinning of the Middle Oreodon sandstone away from the source seems to indicate that the streams emerging from the Black Hills at this time were loaded with coarser sediment than they were, for instance, at the time of the deposition of the Lower Red layer. With an increasing gradient or graded slope away from the hills this coarser sand would be deposited nearer the Hills than would the fine silt of the Lower Red layer. Greater erosion in the Black Hills due to greater precipitation or sudden uplift, or a combination of these factors, may be

the cause of coarser sediment in the Middle Oreodon beds over such wide areas. The sharp delimitation of this sandstone series at the top and base by red clays and caliche beds suggests that the immediate cause of the change in thickness and character of the sediment here is climatically controlled, though regional uplift may have been taking

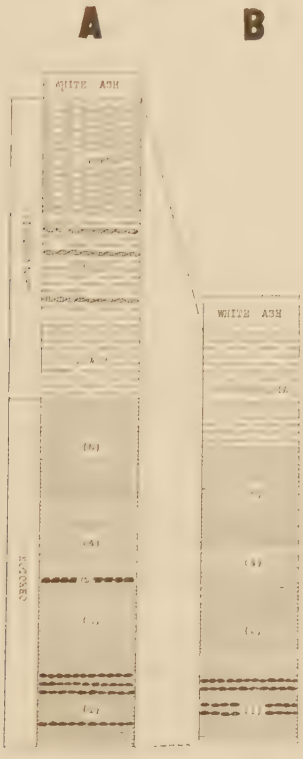



FIG. 9. Parallel sections of the Oreodon and Leptauchenia beds and the White Ash layer in the Big Badlands (*A*), and in the Wall of the Badlands, northeast of Interior (*B*), to show the persistence in thickness of some members of the series and the marked thinning of the Leptauchenia beds and Division 4 of the Oreodon beds. Section *A* is generalized from the Cooney Table Section, Corral Draw, and the Cedar Butte Section, Cottonwood Creek, and Section *B* is detailed. Vertical scale 120′ = 1″.

place at the same time. The change in thickness of the Leptauchenia beds resulting in a thinning away from the Black Hills may have been caused by the streams near the Black Hills carrying a heavier load of

sediment than they would normally, because of the great mass of easily removed volcanic ash on the surface everywhere. Here, again, the streams would be likely to deposit much of their load near the Black Hills. Thus it seems possible to present a reasonable explanation for each case where the deposition is observed to depart notably from its usual uniformity without demanding an "intermittent and recurrent uplift" of the Black Hills, which Ward [85] believes to be the best explanation of the alternation of sand and clay beds in the White River series. In the opinion of the writer, broad and long-continued uplift of the Black Hills took place during the Tertiary and in a general way may have exerted an influence upon the cycles of erosion and deposition during this time, but the sudden changes in the character of the sediment and the short erosional breaks, such as that at the close of Titanotherium time, can best be interpreted as the result of climatic change.

## IV. Volcanic Ash in the Oligocene Formations of the Cordilleran Region.

The presence of volcanic ash as an abundant or dominant constituent of the clastic sediments of the upper White River and Lower Rosebud has been referred to repeatedly. The wide geographical distribution of the White Ash layer has also been mentioned. The source of the volcanic material is a problem which is important in this connection.

It is well known that very extensive vulcanism accompanied the Tertiary orogeny of the Rocky Mountains, and therefore it is not surprising that volcanic ash should be an important constituent of the sediments. Sinclair and Granger [86] describe a level of white tuffs of rhyolitic composition in the Wind River formation along the Beaver Divide of the Wind River basin; a bed of tuff 25 to 75 feet thick in the Bridger in the same section. In the Oligocene (Titanotherium beds) which caps the section there is a dominance of volcanic material, and its structure shows that the source was near at hand. "Extensive volcanic eruptions broke out somewhere in the vicinity, and the first deposit laid down in these troughs was a fine-grained tuffa-

[85] Op. cit., p. 37.

[86] *Bull. Am. Mus. Nat. Hist.*, Vol. XXX., pp. 83–117.

ceous shale. . . . Vulcanism soon became very violent, ejecting great blocks of hornblende andesite, which, with ash, pumice, lapilli, and pebbles and cobbles of pre-Tertiary rocks, were swept down the valleys as mud-flows. The vents from which this material came have not been located. They continued in eruption during the whole of the Lower Oligocene, as here represented, showering the region with dust." Above the agglomerate flow occurs a bed of coarse gravel, and resting unconformably on this are found 528 feet or more of fine buff-colored ash and dust. This ash is generally consolidated by calcareous cement, and becomes increasingly calcareous toward the top of the section. Merriam [87] has shown that most of the clastic sediment of the John Day is ash or volcanic agglomerates, and Darton [88] has described numerous ash layers through the Brulé clays and Arikaree sandstones of the Great Plains, while beds of volcanic ash of Pleistocene age are known as far east as Omaha, Nebraska. Matthew [89] believes that volcanic ash is "almost the principal source of terrestrial sediments in the Tertiary formations of the west."

To return to a consideration of the source of the volcanic material of the Big Badlands, the first to be considered is the Black Hills. The majority of the clastic material of the White River in this area is derived from the Black Hills, and as it is known that laccolithic intrusion was occurring on a large scale in the northern Hills during the Tertiary, eruptive vulcanism is, also, possible. Darton [90] has described "a sheet of obsidian and associated agglomerates which doubtless are the products of surface extrusion . . . 6 miles south by east of Deadwood in the midst of a large area of pre-Cambrian schists. . . . The obsidian is a sheet about 15 feet thick and of small extent. Its smooth lower surface lies on a one-foot layer of impure volcanic ash and is underlain by a thick mass of agglomerates or flow breccia of apparent rhyolitic fragments. This breccia is in masses surrounded by a deposit of finer grained ash which is nearly a square mile in extent. . . . The original vents are

[87] *Bull. Dept. Geol.*, Univ. California, Vol. 2.

[88] U. S. G. S., Prof. Paper 17, pp. 25–43, and plates and figures.

[89] "Problems of American Geology," pp. 389–392, 1915.

[90] *Science*, N. S., Vol. XXXVI., No. 931, "Volcanic Action in the Black Hills of South Dakota," 1912.

not preserved, but their stocks are represented by some of the dikes which occur at many places in the schists or overlying Paleozoic rocks." He suggests that this may show the Black Hills to be the source of part, if not all, of the ash of the Oligocene and Miocene deposits of South Dakota and Nebraska.

A more prolific source of volcanic material, though much more distant, is the volcanic basin of the Yellowstone National Park. Lindgren [91] says of this: "A great center of Miocene (Miocene and Oligocene) activity is in the Yellowstone Park region. Here the eruptions had already begun during the Eocene, but they continued in enormous volume during the Miocene and Pliocene. The early Miocene succession shows andesitic breccias followed by some rhyolite and basalt succeeded by heavy beds of andesitic breccia." In the Yellowstone Park at Specimen Ridge there are in one section from 12 to 15 successive forests buried by showers of volcanic ejecta, one above the other. This gives some measure of the duration of volcanic action in that region.

Griggs [92] has recently published some valuable data on the eruption of Mt. Katmai on the Alaskan peninsula. He presents a contour map of the thickness distribution of the ash from the data available, which gives us a good basis for the estimation of the size of an eruption, or eruptions, necessary to supply the ash for the upper White River and Lower Rosebud ash layers. The map shows a maximum deposition of 50 feet of ash within a mile or two of the volcano, thinning to 10 feet about 10 miles from the volcano, and 1 foot at a distance of 100 miles. At a distance of 300 miles (about that of the Big Badlands) from the Yellowstone Park volcanic basin the maximum thickness of ashfall is less than 0.1 foot. The influence of the prevailing westerly winds on the transportation of the ash is shown by the fact that the contour of one foot of ashfall approaches to within 15 miles of the volcano on its western side, while it extends 100 miles from the center to the east. The amount of material erupted is estimated at 4.75 cubic miles and it is believed to be the largest eruption recorded in human history.

When this is compared with the ashfall of the late Oligocene, the

[91] "Problems of American Geology," p. 270.

[92] "The Valley of Ten Thousand Smokes," *Nat. Geog. Soc.*, 1922, map opposite page 1.

tremendous volume of the eruptions which supplied the latter may be realized. Let us first consider the White Ash layer, which from its uniformity in thickness and character seems to represent practically a pure ashfall over a very wide area, apparently very little reworked by water or mixed with other clastic sediment. This has an average thickness in the Big Badland region of 14 to 20 feet. Darton reports 12 feet at Adelia, Nebraska, and 8 feet in the vicinity of Scott's Bluff, Nebraska, and 6 feet in the Goshen Hole region of eastern Wyoming. With this may be combined a thickness of 75 feet, mostly of volcanic ash, in a Tertiary outlier in the Bighorn Mountains. The upper part of the 528 feet of Oligocene ash in the Beaver divide section of the Wind River basin described by Sinclair and Granger [93] seems to be poorly dated by fossils, and part of it, for aught anyone knows to the contrary, may be of Leptauchenia beds age. A very conservative estimate based on the available data is that the ashfall had an average thickness of at least 10 feet over an area of about 60,000 square miles. This is equivalent to over 100 cubic miles of volcanic material, about 20 times the amount from the Katmai eruption. Consideration of the volcanic material mixed with clastic sediment in the other beds of the later White River and early Rosebud would probably raise the volume of the ash considerably.

Even supposing that this material came from the Black Hills, we find 8 or 10 feet of ash deposited at Scott's Bluff, Nebraska, 200 miles straight south of the possible volcanic vents of the Hills. The products of volcanic action in the Black Hills do not seem of sufficient magnitude to account for more than a limited amount of this volcanic material. Because of the known long duration of volcanic action in Yellowstone Park and the great deposits of Tertiary ash in Wyoming, we may say that, though there is no direct evidence that the White River ash came from this area, it seems to be the most likely adequate source of the volcanic material.

### V. Chalcedony Veins and Sandstone Dikes. Cementation and Silicification of the Sediments.

Through the clays and sandstones of the White River formation occur numerous vertical or but slightly inclined fissures filled with

[93] Op. cit., p. 101.

clay, sand, or volcanic ash, or with thin veins of blue chalcedony. These are not uniformly distributed, some beds having these veins and dikes abundantly developed and others showing almost none, while at the same horizon they may be more abundantly developed in certain districts than in others. The chalcedony veins seem to be more localized than the sandstone or clay dikes.

Hatcher [94] and Lawler [95] have discussed the phenomena exhibited by these dikes and veins and agree in believing that the cracks were formed rather by a desiccation of the sediments of the White River after consolidation than by any general movement of the area, or by volcanic action.[96] As a rule there is no evidence of displacement along these cracks, but Lawler points out one example where a stratum of sandstone was offset about one foot on opposite sides of a massive chalcedony vein, with the surface of the latter slickensided. Similar slickensiding, without evidence of displacement on either side of a vein, is common, the chalcedony having duplicated the slickensiding of the clay wall, or perhaps taken a fibrous structure as the result of slight movement of the walls during the growth of the vein, which may have been due to a wedging apart or reopening of the veins by the deposition of the chalcedony.

It has been generally supposed that the filling of the dikes was from below, as many early investigators believed,[97] but the reverse was clearly demonstrated by the finding of a dike 15 inches in thickness in the Lower and Middle portions of the Oreodon beds filled with pure white ash unmistakably derived from the ash layer nearly 200 feet higher in the series (Pl. IX., Fig. 2). This means that the fissures were cracks open to the surface analogous on a very large scale to mud cracks, formed by the desiccation of a large amount of moist clay and silt, or by the squeezing out of part of the water from these clays by settling. Probably in some cases material was washed away from the side walls of the cracks, as well as washed in from the

[94] *Am. Naturalist,* 1893, Vol. 27, pp. 208–210.

[95] *Am. Jour. Sci.,* Vol. V., Feb., 1923, pp. 160–172.

[96] Diller, J. S., in *Bull. Geol. Soc. Amer.,* Vol. 1, p. 411.

[97] E. C. Case, "Mud and Sand Dikes of White River Oligocene," *Am. Geol.,* Vol. 15, 1895, and Robert Hay, "Sandstone Dikes in N.W. Nebraska," *Bull. Geol. Soc. Amer.,* Vol. 30, 1892, p. 50.

FIG. 1. Vertical clay ridge in middle Oreodon beds, Battle Creek Draw, cut obliquely by a sandstone dyke.

FIG. 2. Dike filled with white volcanic ash cutting Oreodon beds, 5 miles northeast of Imlay, S. D.

surface, indicated by the fact that many dikes show a vertical change in the character of their infilling. Usually the material forming the dikes is a fine silt or sand frequently with a large proportion of muscovite foils, but in a few places coarse stream-worn gravels were found. In one dike in Corral Draw in the Titanotherium beds pebbles rounded by running water and with a diameter of four or five inches were found. These must have been derived from an overlying stream channel of Metamynodon age of which there is now no visible trace. An attempt was made by Mr. Lawler to detect any definite directions or systems of directions which the dikes and veins followed, but there seems to be no marked parallelism between them. Some dikes can be followed in a straight line for a distance of from a quarter to half a mile and thus have quite a dominant influence upon the topography of the region. In the basin of Battle Creek Draw the dikes are abundant in the sandstones of the Middle Oreodon beds, and single dikes are there more continuous than at any other point where they were observed. In this basin there are also numerous faces of clay and sandstone which rise almost vertically from the valley floor. These ridges are frequently 40 or 50 feet high and only about 5 feet in thickness. The only explanation which the writer can offer for these comb ridges is that they owe their resistance to cementation by ground water along joint planes and systems. Plate IX., Fig. 1, shows one of these steep ridges of clay with practically vertical walls on both sides, which is cut diagonally by a conspicuous dike about 8 inches in thickness. The latter can be observed in a straight line for several hundred yards.

As Lawler points out, the genetic connection between dikes and chalcedony veins is clear in that sandstone dikes are often bordered on one or both sides by chalcedony veins. In one place a dike filled with rather coarse sandstone is bounded by greenish slickensided calcite.

An investigation of the lithology of the dike fillings leads to interesting conclusions. The dike fillings from the Upper Oreodon and Lower Leptauchenia beds generally show a fairly high ash content. The dikes are often quite thoroughly cemented and in one case the dike filling was such a tough rock that it was difficult to break it with

a hammer. It had the appearance of a quartzite or a fine-grained volcanic rock. The cementing material of the dikes is found to differ from that of the clays and sandstones of the Oreodon beds in that there is a very small amount of carbonates, averaging from one to eight per cent. The fillings seem to be mostly cemented by silica. In some samples this is in the form of blue chalcedony, while in one or two samples most of the matrix of the sand grains was found to be opaline silica, isotropic under crossed nicols (refractive index about 1.440), and showing a globular or spheroidal structure.

In the preparation of some fossil skulls the clay adjacent to the skulls was found to be cemented with silica into small irregular nodular masses. Graham has shown that the presence of phosphates may cause a silicic acid soil to set to a translucent jelly. Thus the phosphate from the fossil bones is probably responsible for the abundance of these small cherty concretions in their vicinity. The filling of pulp canals of fossil teeth and the marrow cavities of fossil bones with chalcedony, described in an earlier paper, may be caused in the same manner.

The cementation of the dikes with silica, the formation of chalcedony veins, the replacement of gypsum and barite concretions, the filling of marrow cavities and pulp canals of fossil bones and teeth with chalcedony, and finally the silicification of the fresh-water limestones, which are often almost completely replaced, points to an epoch when the ground water was charged with a high amount of dissolved silica.

The period of great ash deposition at the close of the White River and the beginning of the Rosebud seems the most likely time for this. As mentioned above, the ash when deposited was probably strongly charged with acids and water falling on it may have leached much of its alkali content, so that in circulating through the clays below these waters would be strongly alkaline. These waters would be capable of dissolving much silica from the clays and silts and then depositing it after a period of greater aridity. As the many fissures represented the lines of easiest movement for the ground water, they show the greatest effects of this silica deposition and the gypsum and algal limestone were also more easily replaced by the silica than the

rest of the series. It has been observed that in sections where chalcedony veins are abundant the limestone sheet at the base of the Oreodon beds is generally silicified, while in sections away from the chalcedony veins the limestones are largely unreplaced.

It is the opinion of the writer that the distribution of chalcedony veins, the silicification of limestone beds, and the development of caliche layers are all connected with the courses of the rivers of White River time, and this seems to be borne out by the following instances: In Corral Draw, where stream channels are abundantly developed with *Protoceras, Metamynodon,* and *Titanotherium* faunas, there is a strong development of caliche nodules in the Lower Oreodon beds and in the Leptauchenia beds adjacent to the Protoceras channels. The limestone bed at the base of the Oreodon beds is largely replaced by silica and chalcedony veins and sandstone dikes are abundant, especially in the Protoceras channels and the adjacent Leptauchenia beds. This is the only locality at which chalcedony veins were found in the Leptauchenia beds. On the contrary, in the Wall of the Badlands about six miles northeast of Imlay, in the Oreodon and Leptauchenia beds section, no stream channels are present in the Lower Oreodon beds; the Lower Red layer is represented by red clay without a development of caliche nodules; the limestone at the base, though present, is not silicified; there are no chalcedony veins and only one dike was observed, which was filled with white ash, shown in Plate IX., Fig. 2. The cause of this relationship may be the fact that only in the vicinity of the White River streams was the ground sufficiently saturated with water. In the wide interstream areas the sediment would be deposited by occasional flood waters, which would quickly drain back toward the river courses with the end of flood conditions. The silt would be finer in character and with desiccation the deposition of calcareous cement would be insufficient to produce a caliche layer, and with the consolidation of the sediments the contraction in volume would be less because there is less water to be squeezed out or evaporated, hence fissures of desiccation or settling would be smaller and less frequent than in the areas adjacent to river courses where there is more water in the ground to be squeezed out or evaporated. The formation of fissures probably took place at

various times during and since the White River, as the nature of the dike filling in many cases suggests what bed formed the surface at the time of fissure filling. The highest beds exposed in the area, the Lower Rosebud on Sheep Mountain and at the Cedar Pass section of the Wall of the Badlands near Interior, are cut by dikes filled with ash, sand, and clay, showing that fissure formation continued beyond the close of White River time. The chalcedony veins may have been formed during the period when wind-blown ash was the most important clastic constituent of the sediments—*i.e.*, in later White River and earlier Rosebud time. Therefore, though the ash was probably deposited uniformly over the surface of the plain, the silica charged waters from it were only able to move freely through the sediments where the fissures were most frequent, which was in the vicinity of the old river channels.

The streams of White River time seem to have confined their valleys to fairly limited belts, though their actual courses may have shifted two or three miles during the whole of the White River period. The abundant development of channels in the Corral-Quinn-Cottonwood Creek area through all the divisions of the White River and the absence of channels in all divisions in some sections, such as Lower Bear Creek and the Wall of the Badlands northeast of Imlay, seem to indicate this.

## VI. Post-Oligocene History of the Region.

Although this subject lies outside the scope of the present paper, it may be briefly discussed. There are many facts observed in the field which indicate changes of climate and physiography since the deposition of the Rosebud. The stages of erosion, deposition, and climatic change here observed may to some extent be an index of stages throughout the Great Plains province. It is with the hope that this limited amount of evidence may be of value in tracing the full Pliocene-Pleistocene history of the Great Plains that this chapter is written.

*Miocene Deposition.*—As stated above, Miocene deposition in this area is initiated by the White Ash layer at the base of the Rosebud formation, which is preserved only in a few isolated high points

in the area of the Big Badlands, but is continuously exposed south of White River, and according to Matthew [99] reaches a thickness of 500 feet on Porcupine Creek. Middle and Upper Miocene beds are found 60 or 70 miles to the southward in western Nebraska, and may once have extended northward over the South Dakota Big Badlands, although now nowhere preserved there. The fact that isolated buttes in northern South Dakota (Cave Hills, Short Pine Hills, etc.)[100] are capped by Miocene deposits above the White River beds suggests that deposition continued in the belt to the east and northeast of the Black Hills well into the Miocene.

*Formation of the High Plain.*—A period of erosion and peneplanation followed the close of Miocene or Pliocene deposition in which beds of the same age were more eroded to the north than to the south. This is shown by the fact that the present table tops (remnants of this high plain) cut across the slightly tilted edges of the Oligocene beds, so that they are capped by the Pierre shale in the region northeast of Scenic, as near the mouth of Sage Creek, the Titanotherium and Oreodon beds farther south (71 Table, Hart Table, etc.), and by the Leptauchenia and Rosebud beds still farther south (Sheep Mountain, Cooney Table, and the high plain south of White River. This may have been due to a relative depression of the southern portion of the area or relative uplift of the northern portion. After a long period of erosion, during which over 400 feet of sediment were removed from the northern portion of the area, there followed a short period of sedimentation partly of flood-plain character which supplied the 8 or 10 feet of alluvial material which cap the table lands of the region, and rest unconformably on the older White River clays, whose uptilted edges it truncates. Part of this alluvium may have been deposited by eolian action as a prairie loess. The surface of the plain at this time can be pictured by viewing the slightly rolling grass-covered prairie on any of the high table lands above Scenic. For instance, from Cooney Table, which divides White River and Cheyenne River drainage westward from Corral Draw for 15 or 20 miles, it is apparent that Sheep Mountain Table, Hart Table to the north, and the high prairie south of White River,

[99] *Bull. Am. Mus. Nat. Hist.*, Vol. 23, p. 169, 1907.

[100] Todd, Bull. No. 4, S. D. Geol. Survey, 1898, pp. 43–68.

and other distant table lands in all directions, are all parts of an old gently rolling plain. On the sketch map, Fig. 1, the distribution of the remnants of this old plain are indicated by diagonal shading. Data are not yet available for the certain dating of this plain.

*Dissection of the High Plain and Gravel Deposition.*—After the deposition of the surface alluvium a period of rapid erosion ensued. This must have resulted in the entrenchment of the rivers in narrow valleys or canyons. At this period the rivers possessed great power both of erosion and transportation, as they moved pebbles and small boulders from the pre-Cambrian core of the Black Hills fifty to eighty miles out on the plains, where they are found in the White River valley as far down as Interior. Many of these pebbles have diameters of 8 inches to a foot, and all are stream worn and frequently chatter-marked. They are quite locally distributed on the surface of the badland clays, in some localities being so abundant as to form a layer one or two pebbles deep on the surface, while elsewhere not more than 100 yards removed they may be entirely absent. The general trend of these gravel channels is toward the east or southeast, and their materials are very varied. Colorless quartz, rose quartz, feldspar, pegmatites showing muscovite and tourmaline, mica schists and quartz schists, Cambrian quartzites with *Scolithus* borings, Mississippian gray limestones (Pahasapa) with fossils resembling *Straparollus utahensis, Orthotetes inflatus, Camarotœchia* sp., and *Menophyllum excavatum,*[101] and purplish limestones without fossils resembling in appearance the Permian Minnekahta, and softer sandstones, probably of the Cretaceous Dakota-Lakota series are included. Many of the pebbles show a high polish resembling the so-called desert varnish. Ward [102] describes these surface gravels in the Interior section and believes them derived from Protoceras channels of which no other traces now remain. The possibility that these gravels were derived from some of the conglomerates of White River age has been considered by the writer, but not favorably, for pebbles four or five times the size of those generally observed in channels of White River age predominate in these gravels, which are regarded as more

[101] U. S. G. S., Monograph XXXII., "Geol. of Yellowstone Nat. Park," Part II., Plates ———.

[102] Op. cit., pp. 31–33.

recent than the formation of the High Plain and earlier than the Cheyenne River (South Fork) because the latter at present takes all of the sediment from the Black Hills toward the northeast, while these old gravel channels are found far down in the valley of White River. Those found along White River can not be terrace gravels of the modern stream because their pebbles are all derived from the Black Hills, and the present White River does not drain any part of the Black Hills. It would be of interest to know whether or not these gravel beds also crossed White River, but as no work has been done by the recent Princeton expeditions south of White River, the writer can present no evidence on this point.

After the initial stage of river dissection, the materials carried were probably of finer grain and no trace of these later deposits has been observed. There is evidence of terrace formation in isolated flat-topped buttes, such as those along the divide between Indian Creek and Little Corral Draw, which are from 100 to 200 feet lower than the level of the earlier high plain. There must have been a great deal of erosion at this time, and the rivers may have reached a stage of early maturity, when downward progress was interrupted by a more arid cycle. This aridity is indicated by sand dunes mantling an irregular erosion surface of the Oreodon beds at many points. Sand-dune deposits are found on the two isolated flat-topped buttes near the head of Indian Creek mentioned above, and in the line of hills extending east and southeast from Sheep Mountain, and south of Arnold's ranch, where the belt of sand hills is about a mile wide and six or seven miles long.

The coarse gravels which have just been discussed are found in the upper part of the valley of Quinn Draw and about 15 or 20 miles to the northward in the valleys of Indian Creek and Bear Creek, west and north of Scenic. The Bear Creek gravel stream extends through a low gap into the basin of Cain Creek (a tributary of White River) about four miles northeast of Scenic, near the locality where Thaddeus Culbertson made the first collection of fossils from the White River Badlands (*F* on the index map). The general line of sand-hill ridges is roughly parallel to the two stream courses indicated by these gravel beds (east-southeast) and lies about halt way

between them, representing wind-drifted material along the divide between these two streams.

*The Capture of the Black Hills Drainage by the Cheyenne River and the Recent Erosional Stage.*—The next stage of the history of the region was the formation of the modern Cheyenne River, or South Fork of the Cheyenne. This beheaded all the old streams flowing eastward from the Black Hills to the White and Bad Rivers, including those in which the above-mentioned gravels were laid down, and since then the region east of the Cheyenne River has been mainly subject to erosion. The tributaries from the White River and the Cheyenne have dissected the old high plain so completely that it is now preserved only as the various tables and isolated buttes. This erosion has not been uniform, but has been accelerated and retarded by climatic oscillations toward more arid or more humid extremes. When the rainfall is greater than the average, grass and the prairie vegetation begins to work up over the steeper slopes and erosion is greatly retarded, the streams silt up their channels, and flow almost on the valley floor. Then a few years of diminished rainfall kill off the vegetation, the rain in torrential downpours removes the soil, and active dissection again predominates. The streams cut deep, narrow channels with vertical banks in their valley floors, and the older valley bottom is left as a terrace along the side. In the modern badland draws several successive terraces are often visible. In the valley of Bear Creek three terraces were observed along the modern stream. Each one was about 6 or 8 feet in height. These are only minor fluctuations or rhythms of the climate, and may represent periods of only a few years or centuries. There is at least one major break in the erosional history of the Cheyenne River when broad basins seem to have been developed in all of the creek valleys with nearly level floors. The level of this plain is about the top of the Titanotherium beds or the base of the Oreodon beds. Scenic Basin is an example of this type which is still mostly uneroded, though Spring Creek and Bear Creek have begun its dissection. The valley of Indian Creek shows clear evidence of the same plain, in the uniform level of the tops of the rounded Titanotherium ridges. The old basin floor in Indian Creek has been largely dissected, so that the

draws of today flow at a level 100 to 200 feet below it. Plate II., Fig. 2, is a photograph taken on the level of this terrace in Indian Creek, showing the uniformity of levels in the tops of the buttes. The high buttes in the left distance are capped by a sand dune deposited as described above.

Huntington [103] has discussed fully the origin of terraces and shows that while they may be of either tectonic or climatic origin, the actual structures of the terraces would generally demand crustal movement of very unequal distribution acting differently on different parts of each valley and on adjacent valleys, while a climatic change over the whole area more easily explains all the phenomena.

For the terraces formed by the erosion of the remnants of the old high plain by the tributaries of the Cheyenne and White Rivers, a climatic origin is probable, since all the streams seem to show evidence of the same stages of terrace formation. All of the streams now seem to be entrenched in narrow central channels, indicating that the present is a period of greater aridity than usual. The erosion of the high table lands is progressing rapidly and in many places landslips have dropped the outer few feet of the edges of the tables down into the lower badlands. Sometimes this slumping gives rise to temporary ponds, such as are developed in Cedar Pass at Interior, where extensive landslides of the southern face of the Wall of the Badlands have blocked the channels of two or three badland draws.

*Causes of the Capture of Black Hills Drainage by the Cheyenne River.*—Todd [104] in a paper on the hydrographic history of South Dakota suggests that this took place before the Pleistocene because of the amount of erosion since that time by the Cheyenne River. He suggests as causes: "(1) the greater rainfall in the northern Hills; (2) the thinness of the Tertiary beds and more easy erosion of the Pierre shale underlying; (3) the capture of the headwaters of a stream flowing northwards, perhaps the Little Missouri." From the evidence given above it seems that the date of the South Fork of the Cheyenne may be as late as the Pleistocene because of the length of time required for the stage of peneplanation, dissection, gravel deposition, and desiccation described above, which took place between the

[103] "The Climatic Factor," Carnegie Inst. Pub. No. 192, 1914, pp. 23–36.

[104] *Bull. Geol. Soc. Amer.*, Vol. 13, 1902, pp. 31–32.

close of Middle Miocene deposition and the beginning of the Cheyenne River period.

Assuming that the date of the stream capture of the southern Black Hills drainage by the Cheyenne River is in the Pleistocene, there are three possible causes for this capture in addition to those mentioned above by Todd. First, there is evidence that many areas were depressed by the weight of glacial ice. The slope of the South branch of the Cheyenne is in general toward the nearest part of the glaciated region east of the Missouri River. This might be due to a change in the direction of regional slope through the depression of the region under glacial ice. On the map (Fig. 10) it is shown that two other rivers have courses almost parallel in direction to that of the south branch of the Cheyenne. These are the lower part of the Little White River and the upper part of White River. (1) Todd [105] says that there is evidence of an old channel from the sharp northward bend of this river to the Minniechadusa, a tributary of the Niobrara, and that the lower northeastward flowing portion of the stream runs through a narrow canyon for several miles with falls. (2) The upper portion of White River is also parallel in direction to the south fork of the Cheyenne, though the writer has no information as to the date of this valley.

In the northern Black Hills there is also evidence of a general tilting toward the northeast. Mansfield [106] states: "The persistent offsetting of drainage in such a manner as to develop northeast-flowing master streams is not satisfactorily explained by climatic oscillations alone, and appears to indicate northeast trenching." He also recognizes a period of post-Oligocene incision or valley formation, followed by a later period of aggradation when extensive boulder and gravel deposits were formed. He interprets this as a period of relatively high humidity (degradation) followed by a return to more arid climatic conditions (aggradation). This seems to correspond to the beginning of the dissection of the High Plain in pre-Cheyenne River time, followed by the period of heavy gravel deposition in the Big Badlands referred to above, and suggests that these stages may represent significant climatic changes over wide areas.

[105] Op. cit., p. 32.

[106] Mus. of Comp. Zoöl. at Harvard Coll., Bull. 49, 1905–08, pp. 71–76.

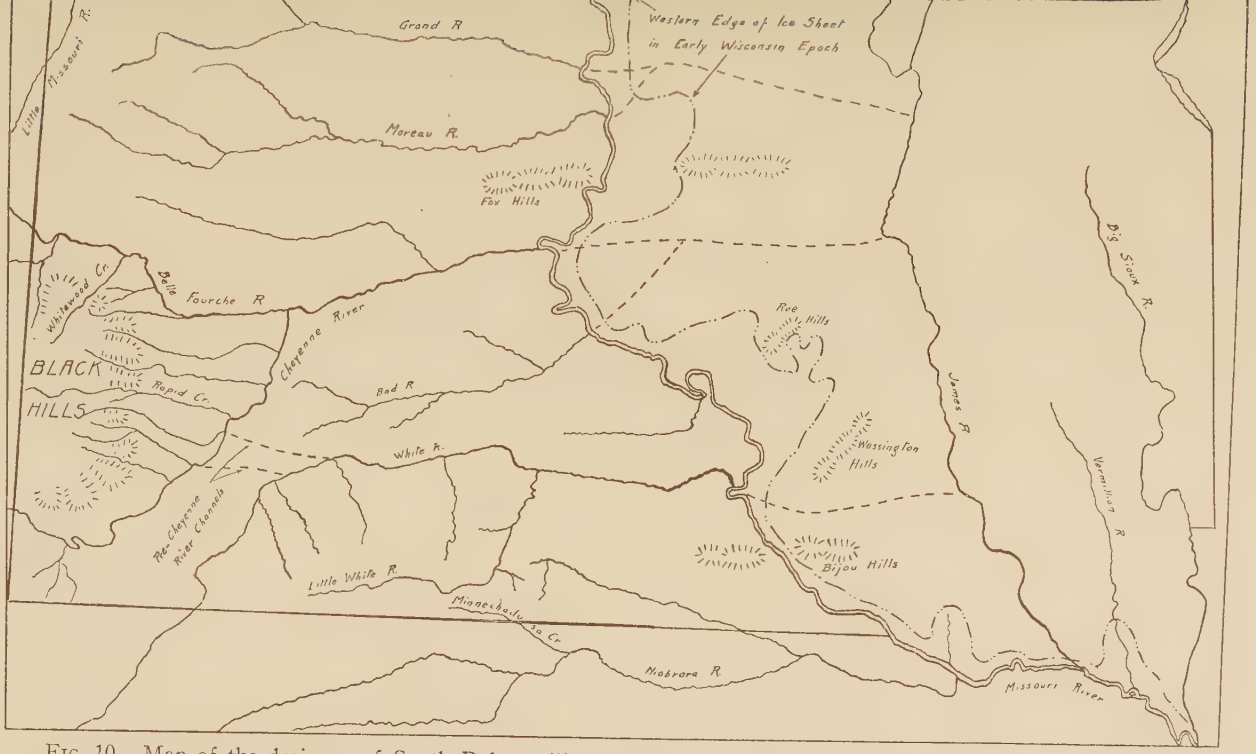



FIG. 10. Map of the drainage of South Dakota, illustrating (1) the stream capture by the Cheyenne River of the drainage of the eastern flank of the Black Hills, which formerly flowed into the White and Bad Rivers; (2) the courses of the pre-Cheyenne River streams now represented by gravel beds, between the Cheyenne and White Rivers; (3) the pre-glacial courses of the Grand, Moreau, Cheyenne, Bad, and White Rivers, east of the present Missouri River, the outlying remnants of the old divides between these rivers, east of the Missouri, and the western edge of the ice sheet in the early Wisconsin epoch; (4) the northeastward courses of Whitewood Creek and the lower part of the Little White River, which have recently captured streams which flowed in an eastern or southeastern direction. Scale 60 miles = 1".

A second possible cause for the capture of the Black Hills drainage by the Cheyenne might be the fact that the Missouri was forced westward nearly 200 miles in central South Dakota by the glacial advance. It had previously flowed in the valley now occupied by the James River in eastern South Dakota. There are remaining east of the Missouri the continuations of high divides between the valleys of Bad River and the Cheyenne, and the White River and the Niobrara (Bijou Hills), showing that these streams flowed eastward beyond the present valley of the Missouri. The course of the Cheyenne River between the Black Hills and the Missouri was shortened more than that of the White River when the Missouri was forced westward around the end of the glacial lobe. Similarly the course of the White River was shortened more than that of the Niobrara. The increased gradients in each case may have stimulated headward cutting of the tributaries, so that they were able to capture the headwaters of streams less favored.

A third cause which may explain the stream capture by the Cheyenne River and the almost complete erosion of the Tertiary deposits from central and northwestern South Dakota, is what Huntington & Visher [107] have described as the shifting outward of a belt of great storminess around the end of a glacial lobe, which is a permanent area of high barometric pressure. If the belt peripheral to the edge of the glacier in central and northern South Dakota received a greater number of storms which had formerly passed north of them, the rivers of this belt, especially the Cheyenne, would be stimulated to more active channel cutting and might easily lower its bed so as to capture the headwaters of streams less favorably situated, as the White and Bad Rivers. The geographic relations seem to suggest some relation between the recent erosional history of the region and the glacial lobe to the east of the present course of the Missouri River through South Dakota.

From the foregoing outline of the post-White River history of the badlands of South Dakota, it is apparent that the series of climatic rhythms traceable in the Oligocene continued in increasing magnitude through the late Tertiary and Pleistocene to the present. It is not

[107] "Climatic Changes," 1922, pp. 110–129, 141–144.

yet possible to interpret these rhythms entirely nor to correlate them with rhythms in other parts of the western United States or the world, but a careful study of the climatic history of different areas may lead to the recognition of many world-wide climatic cycles of lesser magnitude than glacial periods, but still sufficient in size to have a profound influence on the distribution and development of the plant and animal life of the world.